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Snow Roads and Runways

Gunars Abele

November 1990

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Cold Regions Research & Engineering Laboratory

Snow Roads and Runways

Gunars Abele

November 1990

Prepared for
DIVISION OF POLAR PROGRAMS
NATIONAL SCIENCE FOUNDATION

PREFACE

This monograph was prepared by Gunars Abele, Research Civil Engineer, Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The work was funded in part by the Division of Polar Programs, National Science Foundation, under the 1987/88 NSF contract for Antarctic Engineering Services.

The author gratefully acknowledges the assistance of Albert F. Wuori, former Chief, Experimental Engineering Division, CRREL, and current Chief Engineer/Scientist, Keweenaw Research Center, Michigan Technological University. Mr. Wuori, who pioneered much of the research in snow pavement design and construction during the 1950s and 1960s, provided advice and technically reviewed this monograph.

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GUNARS ABELE

INTRODUCTION

The advantages of a compacted snow trail for improved winter mobility were recognized by animals long before man had the need to compact snow for either his personal or his business endeavors. It has been frequently observed that a herd of animals, during migration over terrains covered with deep snow, travel in a single line. Animal trails, produced by repeated traffic by deer or other animals during winter, represent the most basic method for improving the trafficability of a snow surface: compaction. The same procedure for traveling over snow has been practiced by man, first on foot, then on snowshoes, later with dogs or horses and sleds, and eventually with motorized vehicles.

The utilization of compacted snow trails and roads was advanced through a natural evolution process over hundreds of years, but not until almost the middle of this century was any significant effort made to study and understand the behavior of snow. During the last 40 years, extensive field and laboratory studies have greatly advanced the understanding of snow mechanics, specifically the effects of environmental conditions and snow characteristics on the behavior of snow under stress and the changes in snow properties with time. This knowledge has enabled us to develop methods for maximum improvement of the load-bearing capacity of snow pavements.

Canada, the Scandinavian and Baltic countries and the USSR have used a variety of snow trails and compacted snow roads for logging operations for many years. In Canada nearly 50,000 km of snow roads were prepared for logging operations each winter during the 1950s (Ager 1960). During recent years, many thousands of kilometers of snow roads have been constructed annually to serve the Canadian oil and mineral exploration activities (Adam 1978b). In Finland more than 70,000 km of snow roads have been built annually to meet the requirements of the forest industry (Putkisto 1959). These are impressive distances, considering that the entire U.S. Federal Interstate Highway System totals less than 70,000 km, or that a snow road system of 40,000 km would represent a distance equivalent to the circumference of the earth.

The snow trail or road preparation methods in most cases have been crude but effective. Compaction by the traffic itself, the use of a variety of drags and rollers, and in some cases spraying the compacted snow surface with water to increase its hardness have been the basic techniques.

It had been observed that merely disturbing or mixing the original snow layer caused it to harden significantly within a few days. The use of agricultural and improvised harrows, tillers with flails, and open, ribbed or rack-type rollers was introduced for snow disaggregation. This type of snow processing, followed by compaction with rollers and leveling with drags, resulted in snow trails or roads suitable for lumber hauling with either horse- or tractor-drawn sleds.

Early developments in snow compaction equipment in the U.S. during the 1920s and 1930s are illustrated by patents issued for snow packers and levelers (LeValley 1922, Sharp 1931) and published technical papers (Bryant 1923, Blomgren 1932).

The importance of snow as an expedient pavement construction material increased during World War II, when military operations were extended into snow-covered areas where the removal of snow was either impossible or impractical. Very few vehicles were suitable for operations on undisturbed snow surfaces. For expedient roads and runways in areas with a limited snow cover, it was frequently more convenient to compact the snow than to remove it. In deep snow areas it was necessary to prepare a surface snow layer of sufficient

thickness and strength to support wheeled vehicles and aircraft. Rotary soil tillers were introduced for depth processing of the snow, followed by compaction with tractor traffic and rollers and leveling with drags and graders.

The use of snow and ice as runway pavement materials were considered even in more grandiose schemes for military applications. In 1942 Prime Minister Churchill issued a directive to study the feasibility of constructing large floating runways, made of a mixture of wood pulp and frozen water (pykrete), to be used as unsinkable aircraft carriers on the oceans (Perutz 1948). Although the "bergship," requiring almost 2 million tons of pykrete and covering an area of 16 hectares (40 acres), was eventually abandoned, the study did produce a considerable amount of data on the properties of ice and ice–pulp mixtures.

The advent of research activities in Greenland and Antarctica created requirements for snow roads and runways on polar icecaps. A compacted snow airstrip was constructed at the Little America station on the Ross Ice Shelf in 1947 (Moser 1962). Since then, extensive studies on snow pavement construction techniques and design criteria have been conducted in Antarctica by the Naval Civil Engineering Laboratory (NCEL) and CRREL, as well as by Australia and the USSR.

In the 1950s and 1960s, snow processing and compaction tests, using a variety of conventional and specialized equipment, were conducted on the Greenland ice cap and in northern Michigan by CRREL and the Engineering Research and Development Laboratory (ERDL). During this period, similar tests were also conducted in Canada, as well as in the USSR and northern European countries.

Before the 1960 Olympic Winter Games, a 12,000-car, compacted snow parking lot was constructed by NCEL at Squaw Valley, California (Moser 1962).

Snow pavements capable of supporting wheeled aircraft with gross weights in the 70- to 100-ton range have been constructed and used in Greenland (Bender 1957) and in Antarctica (Coffin 1966, Moser and Sherwood 1966, Aver'yanov et al. 1975, 1985).

SNOW CHARACTERISTICS

Strength properties

A schematic outline of the following discussion is shown in Figure 1. The particle or grain size and shape, the arrangement or packing, and the bonding between the particles are the predominant basic characteristics that describe the structure of a snow mass.

Density is the most common quantitative descriptor of snow structure and, to some degree, its strength. However, density is an incomplete descriptor, pertaining primarily to the arrangement or packing of the particles within the snow structure. Other quantitative descriptors, such as the uniformity coefficient, geometric mean diameter and standard deviation, define the particle size distribution in the snow mass.

The snow structure is subject to changes due to time, temperature, wind and solar radiation. Any mechanical disturbance of the snow (disaggregation, compaction etc.) causes radical changes in the snow structure. The structural change that occurs naturally after the deposition of snow and that can be greatly accelerated by mechanical disturbance is an irreversible time- and temperature-dependent process called metamorphism, referred to in the literature as sintering or age-hardening (Bader 1962, Mellor 1964, 1975, Ramseier and Keeler 1966).

Those characteristics that describe the mechanical properties of snow as a material or its behavior under load and that depend on both the structural characteristics and environmental effects can be called the derived properties. These standard mechanical properties (Young's modulus, unconfined compressive strength etc.) can only be estimated from the known structural characteristics (density etc.) and environmental conditions (temperature and time). These properties have to be determined with actual tests, or they can be related to, and therefore represented by, other measured strength indices. For practical engineering applications, various strength indices, some quite arbitrary, can be conveniently obtained and are frequently satisfactory for describing the suitability of snow as a load- or traffic-bearing medium.

Measurement techniques

The strength properties of snow can be determined by various methods and test techniques, depending on the required degree of reliability or the available resources (Abele 1975).

The most reliable method for determining the load- or traffic-supporting capacity of natural or processed snow is by simulating actual loading conditions. Wheel load tests on snow runways require a vehicle that is capable of duplicating various aircraft wheel loads. This involves a specially constructed rig of considerable weight with a hydraulically operated test wheel to allow a convenient method for varying the wheel load. Only in situations where snow runway use is extensive and heavy aircraft are involved could the use of such a vehicle be considered feasible or economically justified.

On snow roads or temporary runways to be used for lighter aircraft where the expected wheel loads are considerably lower, standard wheeled vehicles can be used for test purposes to evaluate the suitability of the

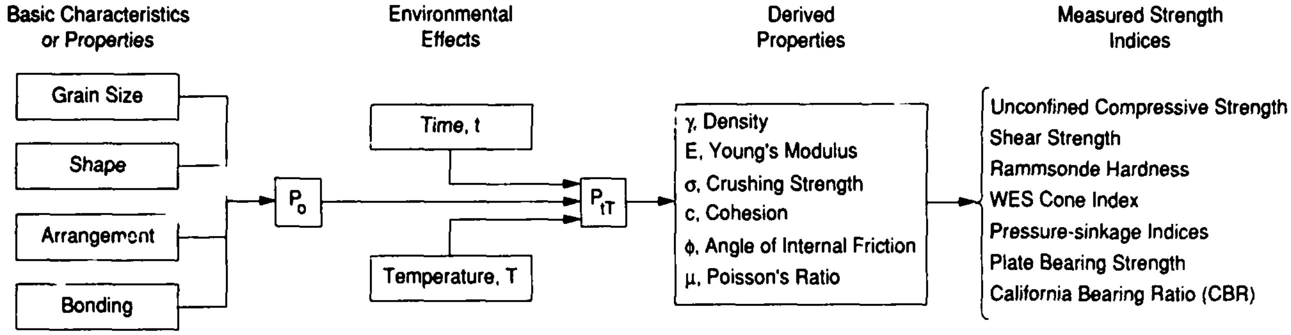


Figure 1. Schematic outline of the various snow strength characteristics.

pavement to support traffic. Moving wheel load tests also permit the detection of weak areas in the pavement that may be missed by any of the other types of tests, which for practical reasons have to be conducted at intervals of considerable distance.

Ordinarily, however, methods other than full-scale simulations are satisfactory for obtaining reliable information required for determining the strength characteristics of snow.

Virtually all of the more practical measurement techniques can be classified into three types, based on their method of operation (Abele 1975):

- *Surface load*, where a vertical load is applied to the snow surface;
- *Sample strength*, where a core sample is removed from the snow and subjected to a strength test; and
- *Probe*, where a probe is penetrated into or through the snow.

The three types of measurement techniques can be considered, by their nature, more simply as bearing tests, strength tests and hardness tests, although the material characteristics determined with each method are strongly interrelated.

Tests that simulate load application to the snow surface (bearing tests) usually produce the most reliable bearing capacity indices; plate bearing and California Bearing Ratio (CBR) tests are in this category. However, these tests are time consuming and cannot always be performed conveniently in the field because of the heavy equipment required.

Conventional strength tests (unconfined, shear etc.) provide meaningful data that can be translated into bearing capacity, and these tests can be performed in the field with portable equipment. But sample (core) preparation does require some time and care, and in the case of snow roads and runways, sample removal leaves holes in the pavement.

Tests conducted with various probes or cone penetrometers provide indices of the resistance to penetration (hardness). These tests are the most convenient and least time consuming; in addition they provide a vertical hardness profile of a snow layer or a snow pavement. The hardness values, however, have no real physical meaning; they are simply indices of the "relative hardness" of snow and have to be correlated empirically with more meaningful or familiar strength properties or actual bearing capacity.

Not surprisingly the degree of ease with which a test can be performed is related inversely to the degree of reality with which a load application to snow is simulated (Fig. 2). A plate bearing test, which simulates a load application more closely than any of the other tests (except an actual wheel load test in the case of a road or a runway), is the most time consuming one to perform. A test in which a relatively thin probe is penetrated into the snow layer or pavement is the easiest to perform but the least representative of a load application.

The various snow strength tests which have been used or could be used to evaluate bearing capacity of snow are discussed individually below.

Plate bearing tests are usually conducted by applying a constant load to a plate and measuring the settlement with time, or a constant rate of either penetration or stress increase can be used. These tests have been used for studying the mechanical properties and behavior of snow as a material, specifically the creep characteristics (viscous flow) of snow under sustained loading, the characteristics of deformation and stress distribution under a uniform load (pressure bulb configuration), and the nature and mechanism of snow failure (Wuori 1957, 1962, Abele 1967, Russell-Head and Budd 1989). For simulation of heavy aircraft wheel loads, plate bearing tests require corresponding reaction load capability; D-8 tractors or equipment of comparable size have been used in field tests (Fig. 3). Even when this equipment is available for these types of tests, its use for evaluating snow pavement strength properties may not be desirable because of the potential damage it could inflicted to the pavement.

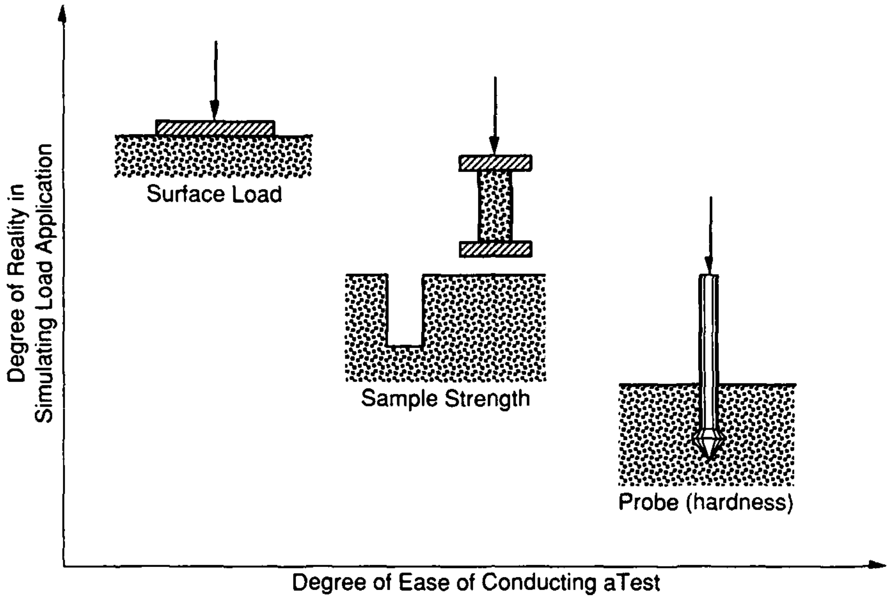


Figure 2. Relative degree of reality in simulating load application vs the relative ease of a test method.

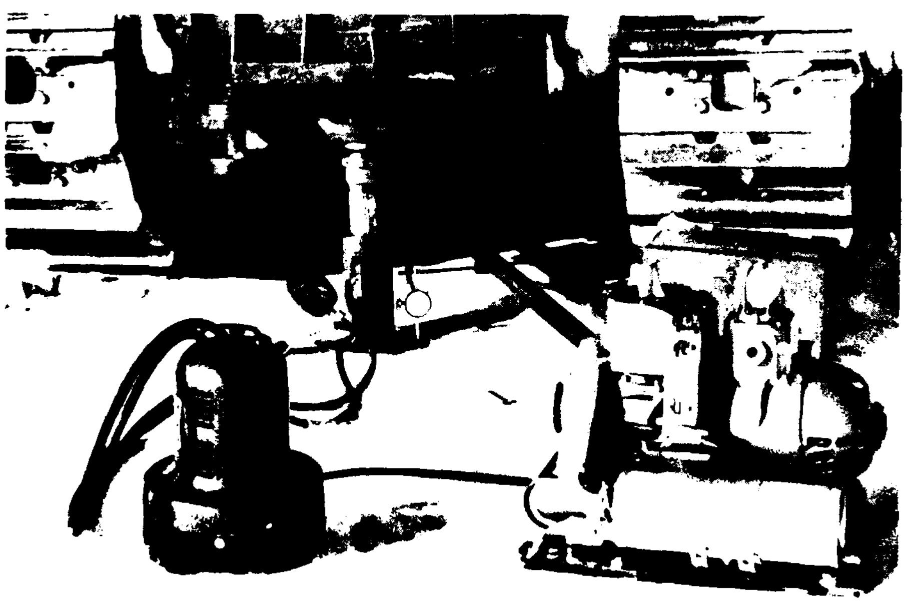


Figure 3. Plate bearing test.

The CBR test, standard for soils, is a constant-rate-of-penetration test using a 19.35-cm^2 (3-$in.^2$) circular piston (Fig. 4). The CBR value is obtained by taking 10% of the unit load required to cause a penetration of 0.25 cm using a penetration rate of 0.13 cm min^{-1}. The CBR test requires the same type of heavy equipment or reaction frame as the plate bearing test, and it does not permit convenient or quick evaluation of pavement bearing strength (Wuori 1963a). But because of its extensive and accepted use in determining the bearing capacity of soils, CBR values provide a familiar and meaningful indication of pavement strength to a civil engineer. However, because of the relatively small loading area, the CBR test is not suitable for soft snow.

The unconfined compressive strength test can be conducted in a coldroom (Fig. 5) or in the field with manually operated portable equipment (Abele 1963). Preparation of test samples, usually obtained with a 7.6-

Figure 4. California Bearing Ratio (CBR) test.

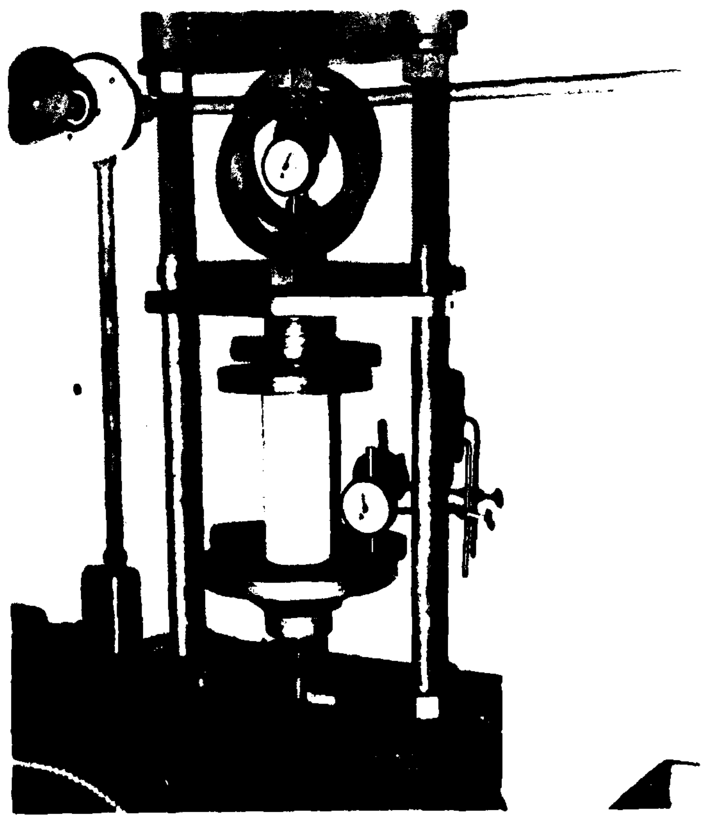


Figure 5. Unconfined compressive strength test.

Figure 6. Snow core auger.

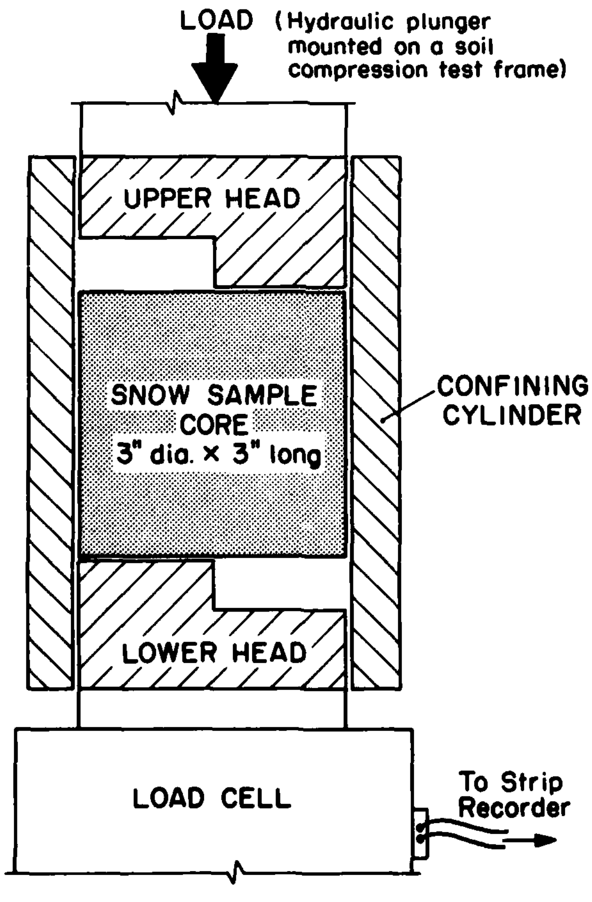


Figure 7. Cross section of NCEL shear test apparatus.

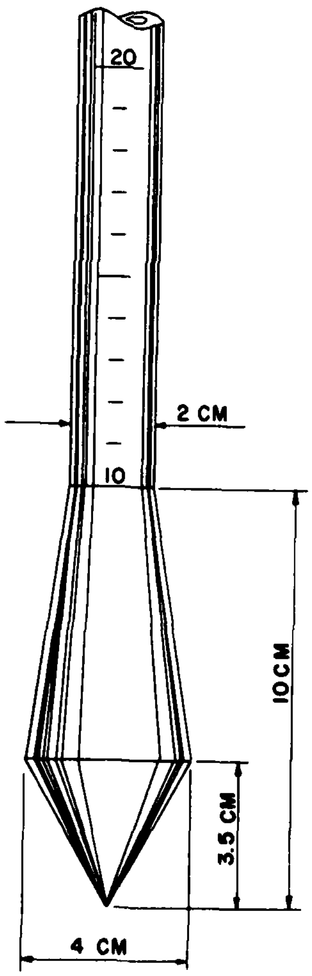


Figure 8. Rammsonde penetrometer cone.

cm coring auger (Fig. 6), can be time consuming, since some care is required to ensure that the sample ends are smooth and perpendicular to the core axis. The data provide meaningful crushing strength values of the material in familiar engineering terms.

The confined shear strength test was developed by the Naval Civil Engineering Laboratory (NCEL) for use on snow pavements that are too hard for manually operated penetrometers (Moser and Stehle 1964). The test is less time consuming than the unconfined compressive strength test, since care in sample preparation for this test is less critical. The test, which measures the strength of a snow core when sheared vertically through the center of the core (Fig. 7), has been used extensively in Antarctica for evaluating the wheel load supporting capacity of snow roads and runways (Moser and Sherwood 1966, 1967b).

The triaxial compression test, which simulates surface load application better than the unconfined or shear strength tests, has been used in soil mechanics and, to some degree, in snow mechanics to obtain *c* (cohesion) and ϕ (angle of internal friction) values. It is one of the most inconvenient and time-consuming tests when performed in the field.

Ram hardness of snow is determined with the Rammsonde cone penetrometer (Abele 1963, Ueda et al. 1975). The hardness value indicates the resistance offered by a snow layer to the vertical penetration caused by ramming a metal cone of given dimensions with a drop hammer of known weight from a given height (Fig. 8, 9). Hardness readings can be taken at any desired depth increment. This test has been the most widely used method for evaluating the strength properties of snow runways (Wuori 1960, 1962a, 1963a, Abele et al. 1966, Abele 1968, Lee et al. 1988, Russell-Head and Budd 1989). The test is relatively simple and less time consuming than most of the other tests; therefore, it permits the collection of a greater amount of data and better coverage of a snow runway or road pavement.

Since the standard 60° cone is not suitable in extremely hard snow pavements, 30° cones have been used, most recently in Antarctica (Lee et al. 1988). The proce-

Figure 9. Rammsonde penetrometer in use.

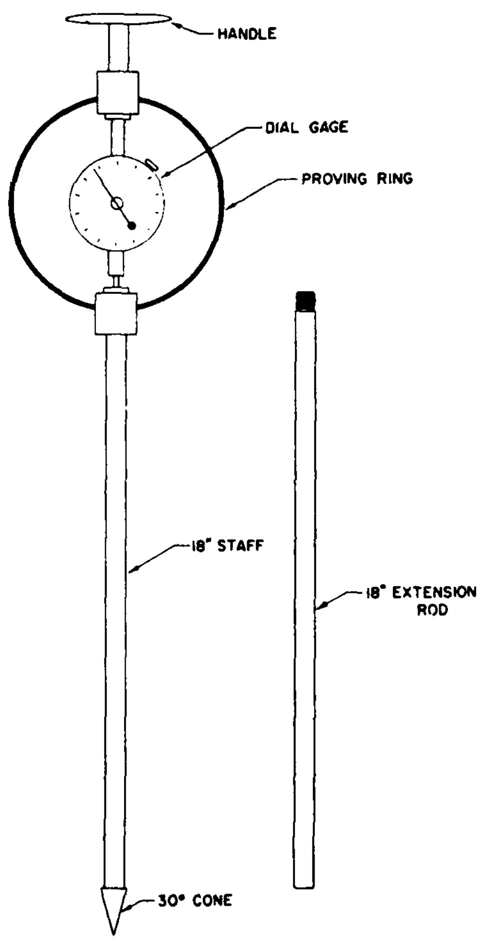


Figure 10. WES cone penetrometer.

Figure 11. Clegg impact device.

dure for computing the ram hardness values and the correlation between the 60° and 30° cone hardness values are shown in Appendix A.

The WES Cone, developed by the U.S. Army Corps of Engineers Waterways Experiment Station, has been used for assessing the trafficability characteristics of soft soil and natural snow covers (Fig. 10). Since this is a hand-pushed device, it usually cannot penetrate into most processed and compacted snow pavements.

The hydraulic probe was developed by NCEL for rapid determination of snow pavement hardness (Moser and Stehle 1964). The device, a 2.2-cm-diameter blunt-tipped rod, is penetrated rapidly into the snow pavement with a ram operated from the hydraulic system of a small snow tractor. The resistance to penetration is recorded mechanically on a data card, giving a vertical hardness profile. In principle, this type of test would be desirable because it is quick and relatively simple. The great number of tests that can be performed in a short time may outweigh its deficiencies (a vehicle is required and it does not simulate a wheel load application), once a reliable relationship is established between the probe data and the actual traffic bearing capacity. However, this method was not pursued by the developer past the initial (and apparently promising) experimental stage.

The Clegg impact device, developed to supplement the CBR test, measures the deceleration of a standardized drop hammer upon impact with a soil (or snow) surface (Fig. 11). The Clegg impact value (CIV) has been correlated with the CBR for soils (Clegg 1983). Since the Clegg impact test is more convenient than the CBR test for evaluating the surface strength of a snow pavement, the device has recently been used on snow roads and runways in Antarctica (Lee et al. 1988).

Most other penetrometers, probes, shear vanes and the bevameter, used for estimating snow properties related to vehicle mobility, are not suitable for use on hard snow pavements (Abele 1975). The various manual hardness gauges, such as the Proctor needle (Ager 1959), the Canadian hardness gauge (USACRREL 1962), the drop cone (Inaho 1955) and the hardness gauges used in the Soviet Union in the 1940s (Kragelskii 1945a) (Fig. 12), are suitable for measuring only the snow surface hardness and do not necessarily provide any reliable indication of the strength or the load-bearing capacity of the snow pavement as a whole.

Density is relatively easy to measure from snow core samples (Fig. 13) and can be used as a rough index for determining the degree of compaction and therefore the potential strength of a snow pavement. But unlike snow strength, the density of compacted snow does not change with temperature and time; therefore, density alone cannot be used as a reliable index of snow strength without considering temperature and time effects.

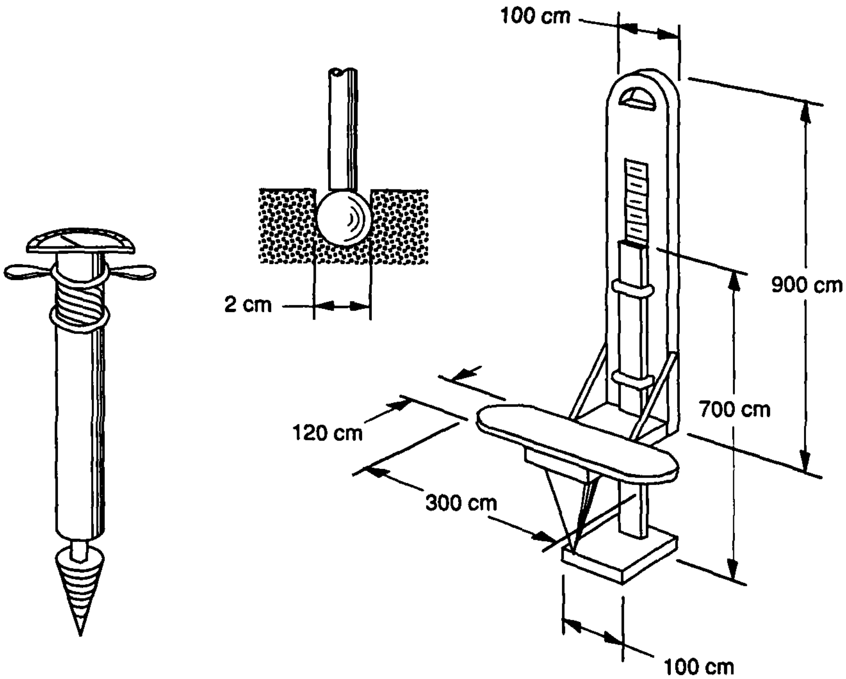


Figure 12. Various Soviet snow hardness devices.

Figure 13. Obtaining a snow core.

For practical field use in determining the load-bearing capacity of snow pavements, the Rammsonde cone penetrometer has been the most commonly used instrument. A sufficient number of ram hardness measurements can be made during a few hours (a typical rate is 10 measurements per hour) to obtain a representative sample of the snow hardness properties of a road or runway section several hundred meters long. Ram hardness data have been correlated with other snow strength properties and actual wheel load supporting capacities of snow pavements. These relationships will be discussed later.

The unconfined compressive strength test has also been used, but not as extensively as the ram hardness. Only one or two strength profiles (using four to five test samples per 1-m pavement thickness) can be obtained during one hour.

Grain size

The size of snow crystals varies greatly, depending on the atmospheric conditions during precipitation, wind, temperature during the subsequent metamorphism, overburden pressure and age.

As in soil analysis, the grain size distribution of snow is ordinarily plotted in terms of the cumulative percent finer (by weight) vs the sieve opening size (on a log scale), resulting in a typical S-shaped grading curve (Fig. 14). When the data are plotted on a log-probability graph, the grain size distribution can usually be repre-

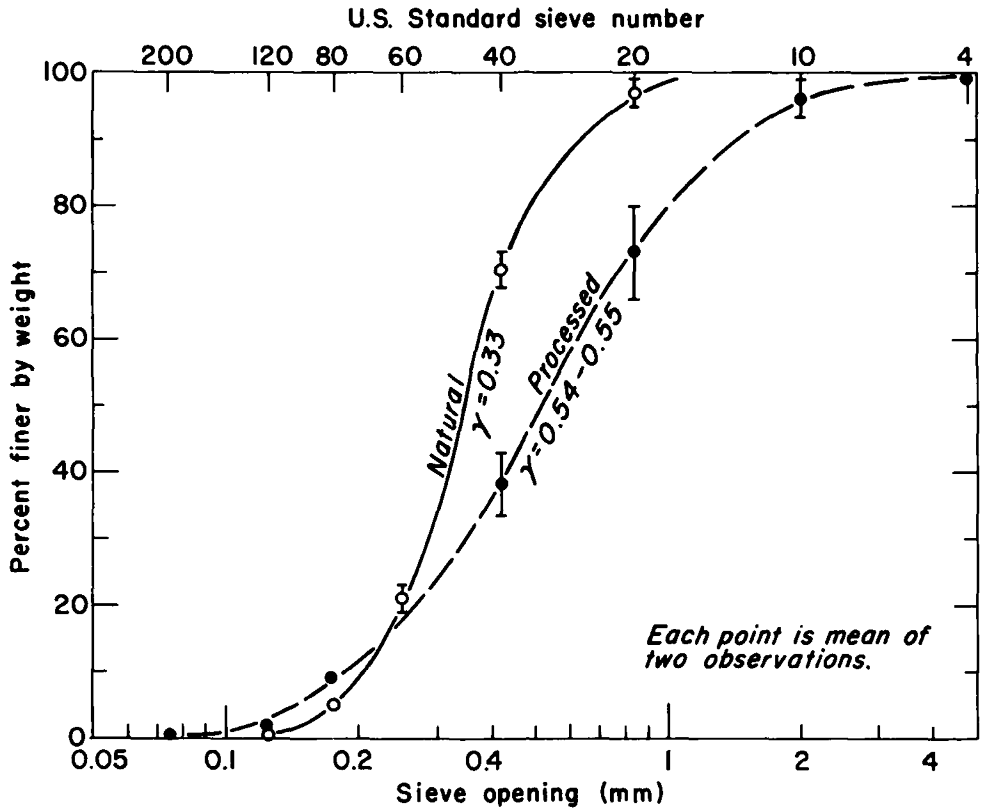


Figure 14. Particle size distribution of snow (Abele 1967).

sented reasonably well by a straight line for almost the entire size range (Fig. 15).

After deposition, during the process of metamorphism, gradual grain growth occurs, primarily as a result of sublimation, and intergranular bonds form by sublimation and diffusion. Therefore, older snow has coarser grains than fresh snow. This process is illustrated in Figure 16. The thin-section photographs show snow samples with the same density (0.51 g cm^{-3}) obtained from the Greenland ice cap at three ages: approximately 10, 14 and 20 years after deposition (Waterhouse 1962).

The range of the grain size distribution of snow disaggregated with various snow millers or rotary plows is shown in Figure 17. The geometric mean diameter M (grain size at 50% finer by weight) is in the 0.4- to 0.9-mm range, and the uniformity coefficient c_u (represented by the slope of the line) is in the 2.0 to 2.3 range. These values represent the grain size characteristics of snow within a few hours after disaggregation. The subsequent grain growth and bond formation are greatly accelerated by the disaggregation and the resulting densification. The density achieved by snow milling and compaction (0.5 g cm^{-3} or more) is equivalent to that caused by overburden pressure and settlement in a perennial snowpack, such as Greenland or Antarctica, after 10–20 years.

Effect of time and temperature

The strength of snow generally increases with an increase in density, with time, and with a decrease in temperature.

The effect of temperature is illustrated in Figure 18, where the relative strength of ice (represented by the ratio of the strength at any temperature to the strength at –10°C) is plotted vs temperature (Mellor and Smith 1966). The rate of the strength increase is between 15 and 20% per 10°C drop in temperature, based on the strength at –10°C.

The effect of time on the increase of strength of disaggregated, compacted snow is shown in Figure 19. The rate of the strength increase decreases with a decrease in temperature (Ramseier and Sander 1965). That is, the lower the temperature, the slower the rate of strength increase (age-hardening). However, the snow at the lower temperature will ultimately reach a higher strength than that of the snow that has been age-hardened at the higher temperature. For example, a disaggregated, compacted snow with a density of approximately 0.5 g cm^{-3} that has been age-hardened at a constant temperature of –10°C reaches an unconfined compressive strength of 10 kg cm^{-2} in approximately 2–3 weeks. At a constant temperature of –40°C, more than 3 months is required for snow of the same density to reach the same strength.

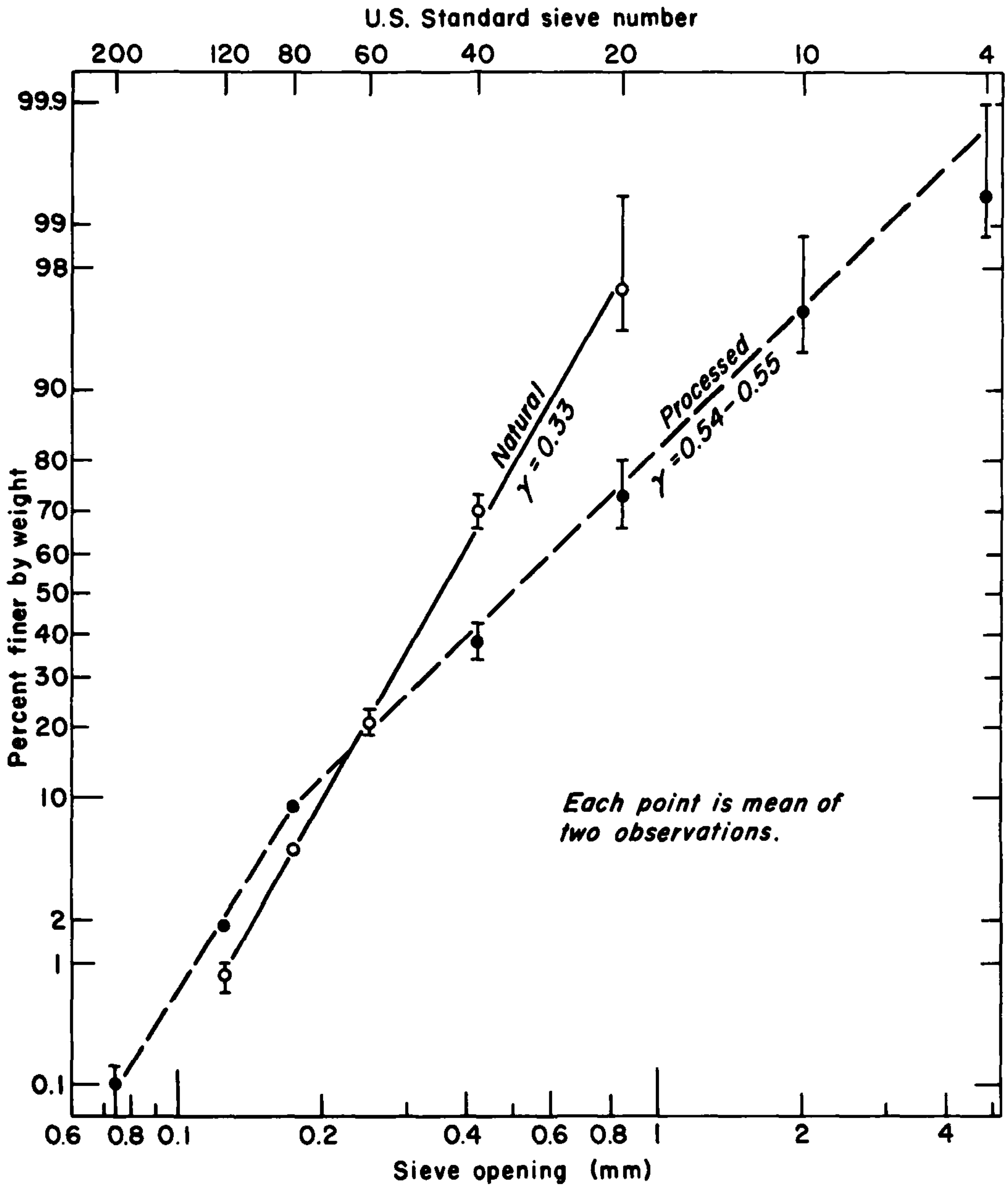
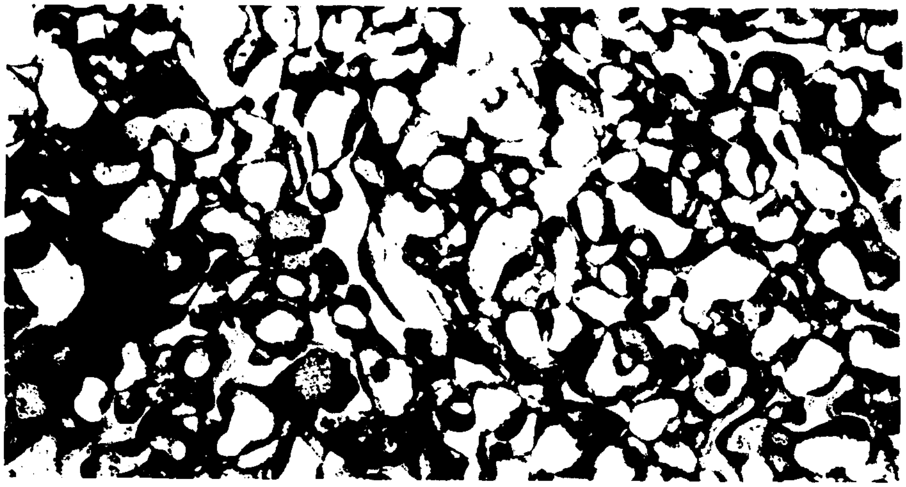
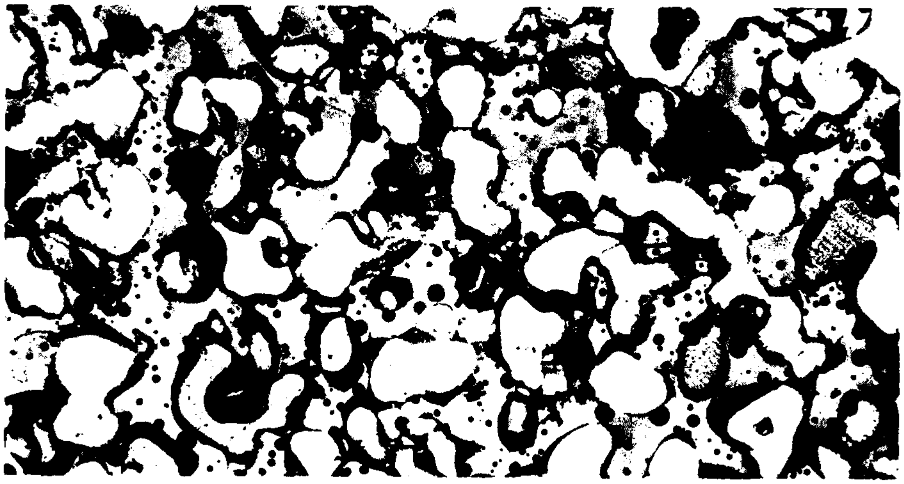


Figure 15. Log–probability plot of the particle size distribution of snow (Abele 1967).

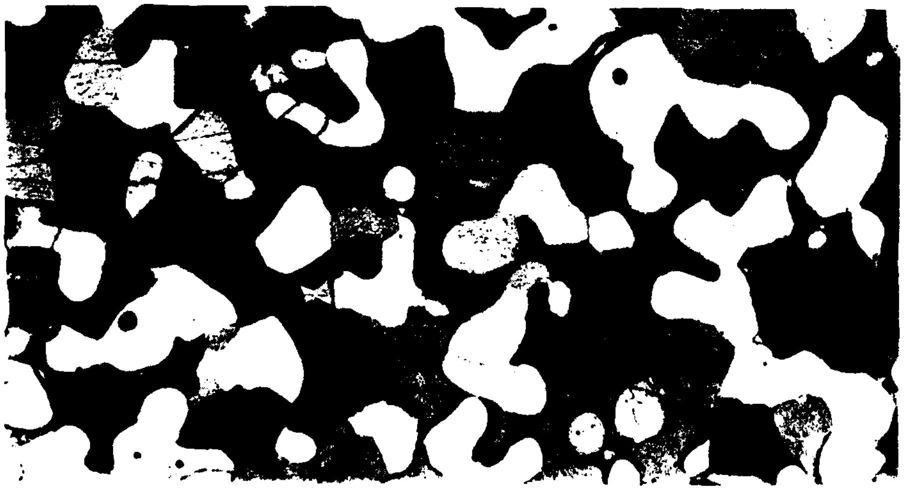
The snow at −10°C will continue to increase in strength slightly for a few more weeks, approaching its ultimate strength for this temperature and density (less than 12 kg cm^{-2}). At −40°C, snow of the same density will continue to increase in strength at a slow and constantly decreasing rate for another year or more before approaching its ultimate strength for this temperature (between 16 and 18 kg cm^{-2}). The curves in Figure 19 were obtained from laboratory tests where the temperature could be closely controlled. In the field the age-hardening process of a recently constructed snow pavement is subjected to natural temperature variations. An increase in temperature during the early stages of the age-hardening process tends to increase the rate of strength increase but decrease the potential ultimate strength of the snow pavement. A decrease in temperature shortly after the snow pavement construction will have the opposite effect. Changes in temperature during the later stages of the age-hardening process will influence primarily the strength of the snow pavement, having very little or no effect on the rate of any further strength increase. Therefore, the relative effects of time and temperature on the strength of a processed snow pavement suggest very clearly the most effective construction procedure.



a. 10-year-old sample from 7.96 m below the snow surface.



b. 14-year-old sample from 9.71 m below the snow surface.



c. 20-year-old sample from 11.94 m below the snow surface.

Figure 16. Snow grain size growth with time (Waterhouse 1962).

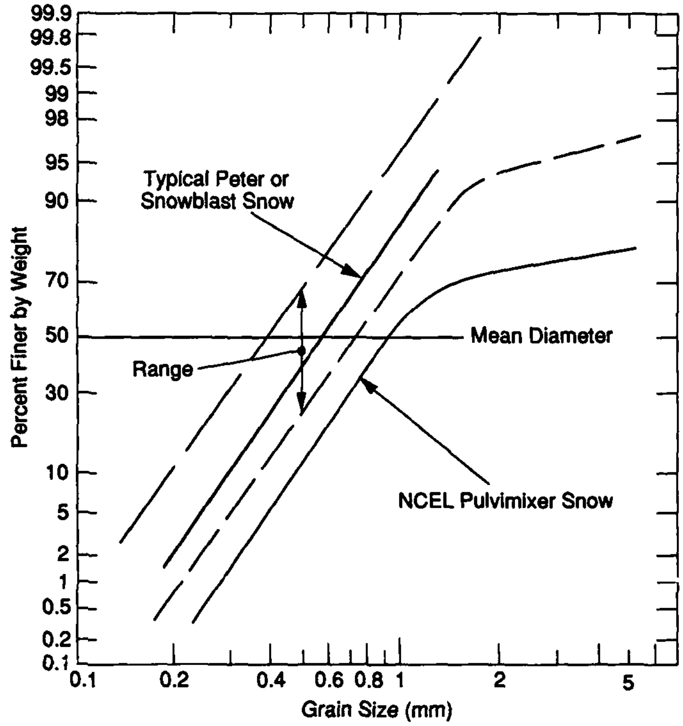


Figure 17. Particle size distribution of mechanically disaggregated snow. The data were obtained a few hours after processing.

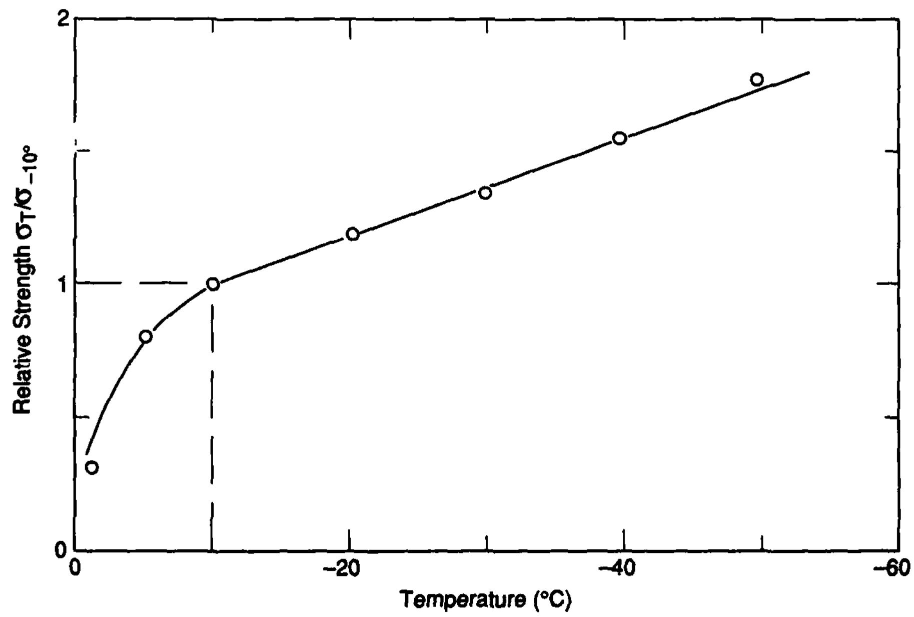


Figure 18. Effect of temperature on ice strength. (From Mellor and Smith 1966.)

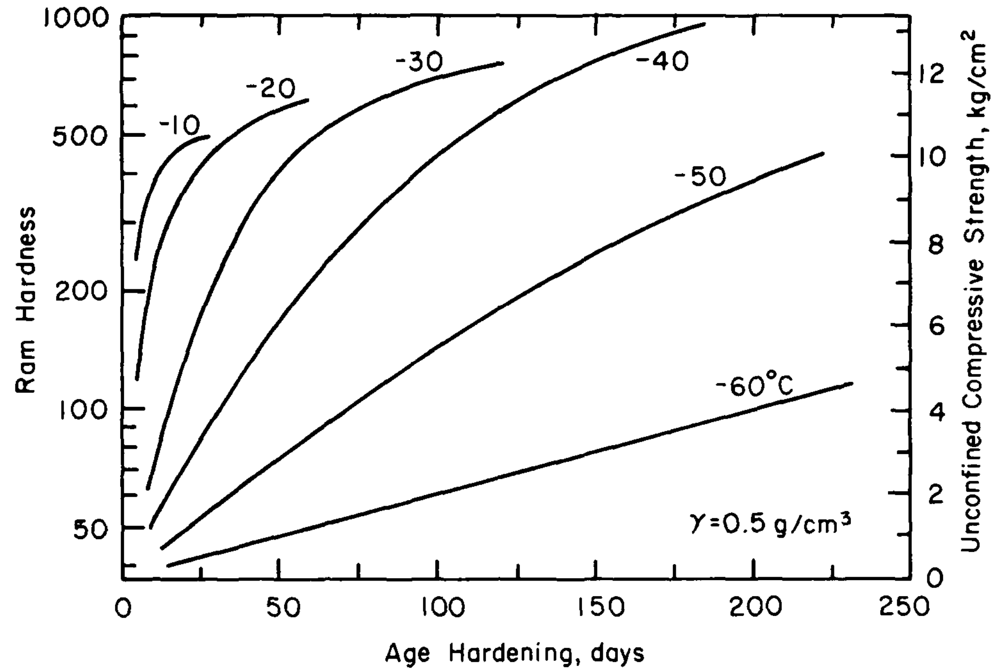


Figure 19. Effect of time on the strength of processed snow as a function of temperature.

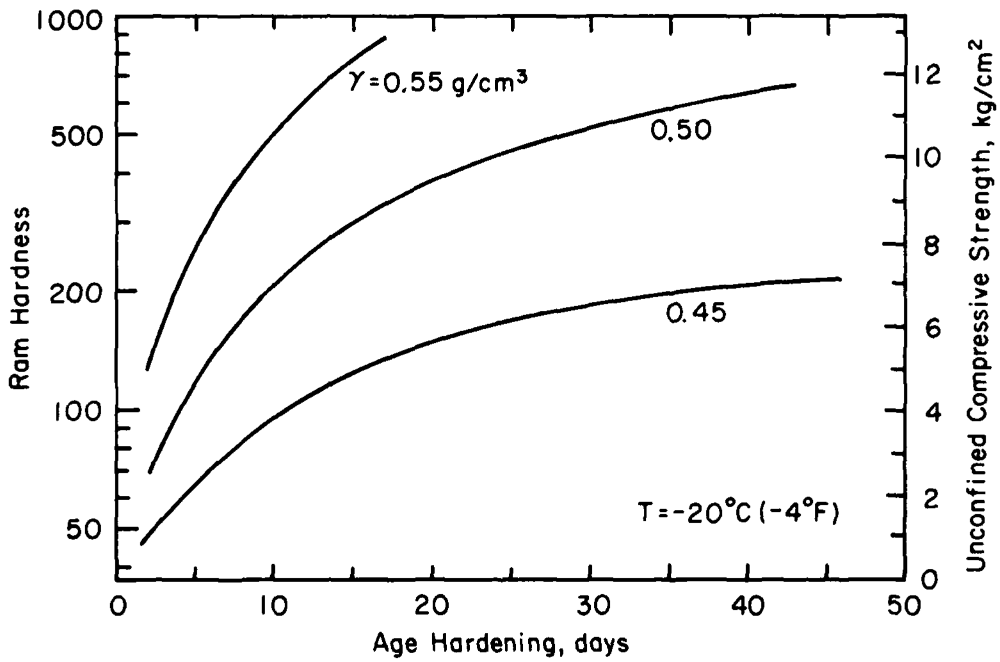


Figure 20. Effect of time on the strength of processed snow as a function of snow density.

The effect of the initial snow density, achieved during compaction, on the snow strength with time is shown in Figure 20. For the same temperature and time conditions, a higher initial density will result in a higher strength.

The ideal conditions, which would take the maximum advantage of the time and temperature effects, are

- Relatively high temperature during the snow disaggregation and compaction activities and during the early stages of the age-hardening process (–5° to –10°C is ideal), which will result in a higher initial density and the maximum rate of age-hardening; and
- A decrease in temperature when the age-hardening process is nearing completion (or has, for all practical purposes, ended), which will result in a further increase in strength.

The combined influence of temperature and initial density on the strength increase with time is illustrated in Figure 21.

A number of studies have been conducted on the sintering or age-hardening process of snow to develop the theory and the mathematical expressions for this process (Butkovich 1962, Gow and Ramseier 1963, Ramseier and Sander 1965, Ramseier 1966, Ramseier and Keeler 1966). For practical field applications related to snow road and runway construction, the strength increase with time can usually be expressed as a function of the logarithm of time, at least for the first few weeks of the hardening process:

$$\sigma = n \log t + b \tag{1}$$

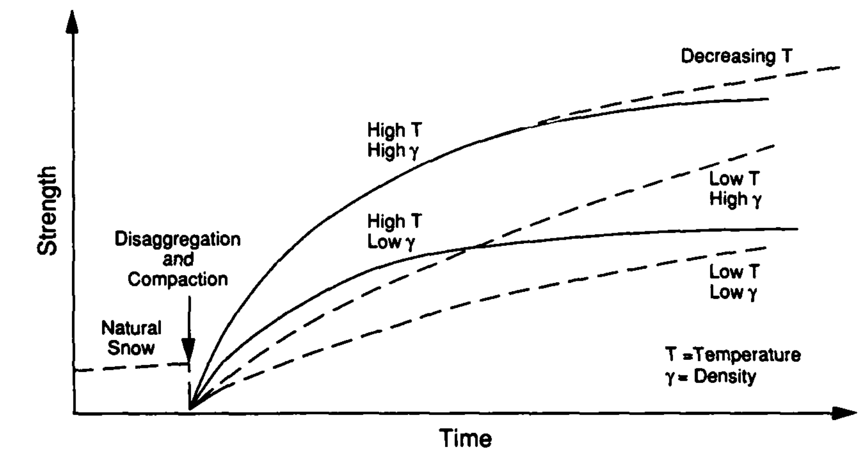


Figure 21. Combined effect of time and temperature on the age-hardening processes of snow.

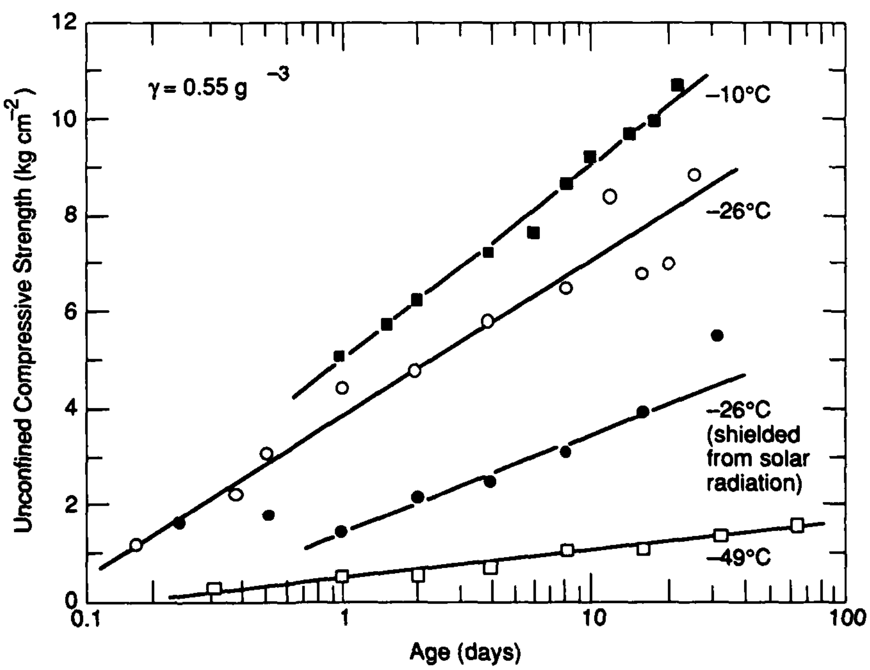


Figure 22. Strength increase with time at various snow temperatures. (Data from Gow and Ramseier 1963, Ramseier and Sander 1965).

where σ = unconfined compressive strength
n = rate of strength increase
t = time ($1 < t < 30$ days)
b = intercept.

Typical examples of strength increases with time for disaggregated, compacted snow with a density of 0.55 g cm^{-3} at temperatures of $-10°$, $-26°$ and $-49°C$ are shown in Figure 22 (data from Gow and Ramseier 1963, Ramseier and Sander 1965). The effect of shielding from solar radiation is also illustrated. Samples shielded from direct solar radiation gained strength at a lower rate than those exposed to solar radiation at the same ambient temperature.

Figure 23 shows a semi-log plot of the age-hardening process in terms of the work required to disaggregate high-density snow vs time.

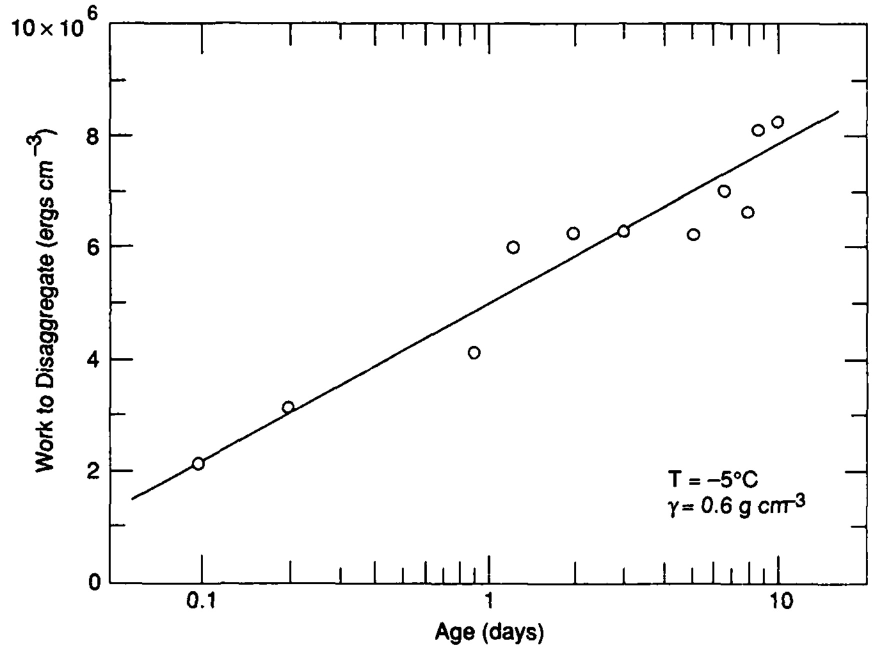


Figure 23. Work required to disaggregate snow vs time. (Data from Bender 1957.)

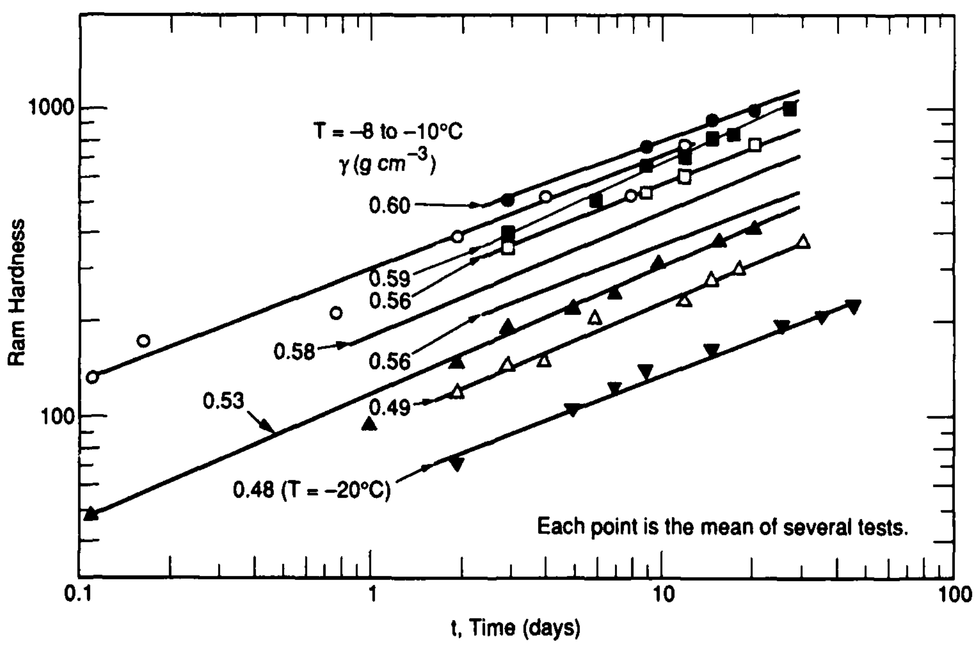


Figure 24. Ram hardness vs time as a function of snow density.

Rammsonde hardness vs time for snow in the 0.49- to 0.60-g cm^{-3} density range at relatively constant high temperature (–8° to –10°C) is shown in Figure 24. The data represent the mean hardness for the top 0- to 20-cm thickness of various snow pavements in Greenland (Wuori 1960, 1963a, Butkovich 1962), Antarctica (Abele 1968) and Michigan (Wuori 1959). The ram R vs time t data are plotted on a log–log graph, and the relationship can be expressed by

$$R = btn. \quad (2)$$

The slopes n of the R vs t lines are in the 0.34–0.40 range. That is, the ram hardness for this density and temperature range increases at a rate somewhat higher than the cube root but less than the square root of time (for t between 1 and 30 days). The intercept b at $t = 1$ is primarily a function of the initial snow density achieved during compaction.

Interrelationships between snow properties

The relationship between unconfined compressive strength (at –10°C) and density of naturally densified snow is shown in Figure 25. The envelope represents the range of data from the snow profile on the Greenland ice cap (Butkovich 1956, Mellor 1966), where the density is the result of overburden pressure, depending on the depth below the surface.

Figure 26 shows the strength vs density relationship for mechanically disaggregated (processed) and compacted snow after approximately two weeks of age-hardening at –10°C. The unconfined compressive strength data do not represent the ultimate strength of the snow for the density range shown, since the hardening process has not been completed. The envelope represents the range of unconfined compressive strength at –10°C that can be expected in a snow pavement a couple of weeks after construction (Brunke 1959, Wuori 1960, 1963a, Abele 1963).

The corresponding relationship between ram hardness and density for the same snow and the same temperature and time conditions is shown in Figure 27. As in the previous figure, some increase in the ram hardness can be expected during the following two or more weeks before the age-hardening process is completed.

Unconfined compressive strength vs ram hardness data, obtained from various processed snow pavements, are plotted in Figure 28. In the initial data analysis (Abele 1963) the unconfined compressive strength σ (kg cm^{-2}) was expressed as a function of the logarithm of ram hardness R:

$$\sigma = 4.1 \ln R - 14.7. \quad (3)$$

The number of data points was 482, the coefficient of correlation r was 0.84, and the standard deviation of σ was 2.4 kg cm^{-2}.

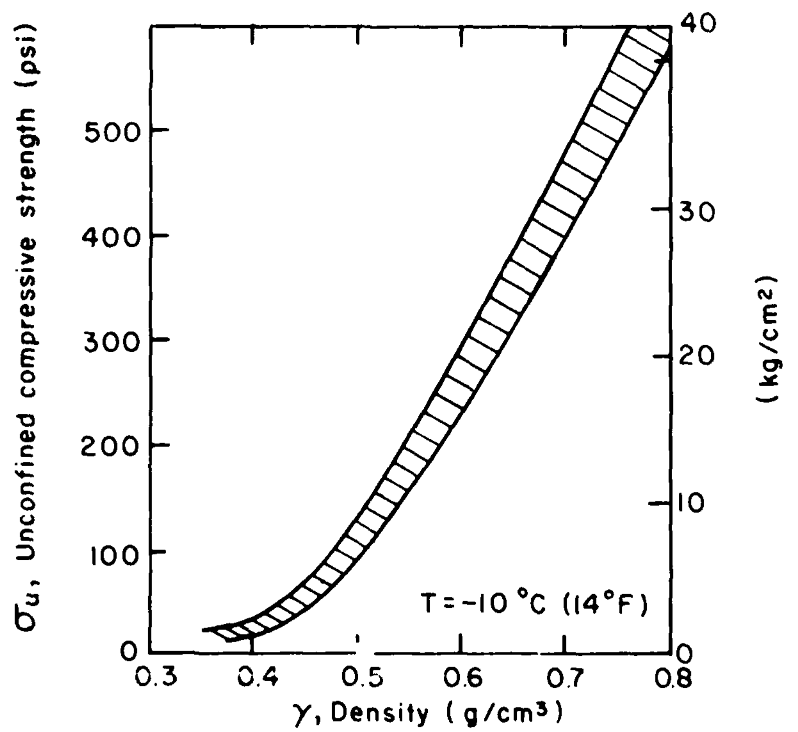


Figure 25. Unconfined compressive strength vs density for natural snow.

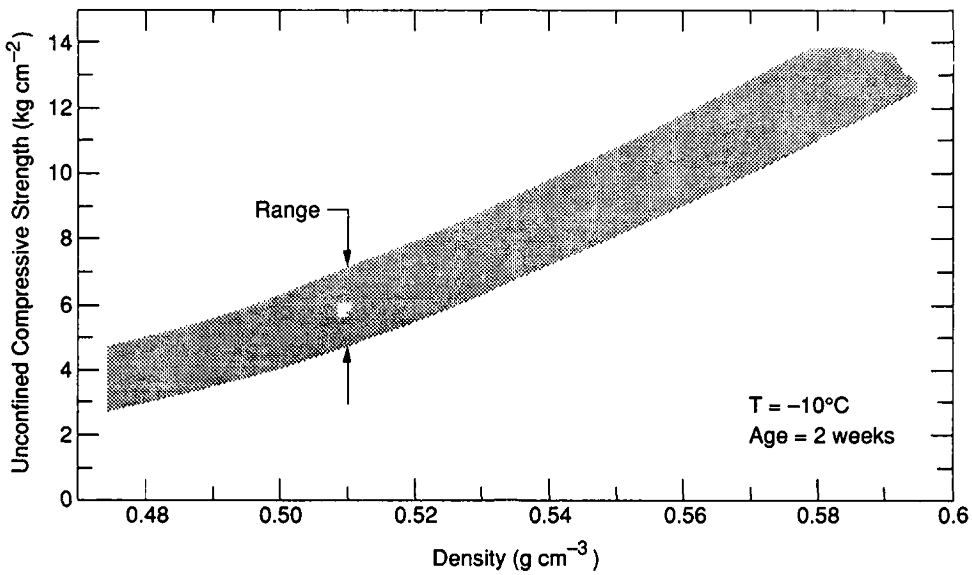


Figure 26. Unconfined compressive strength vs density for processed snow.

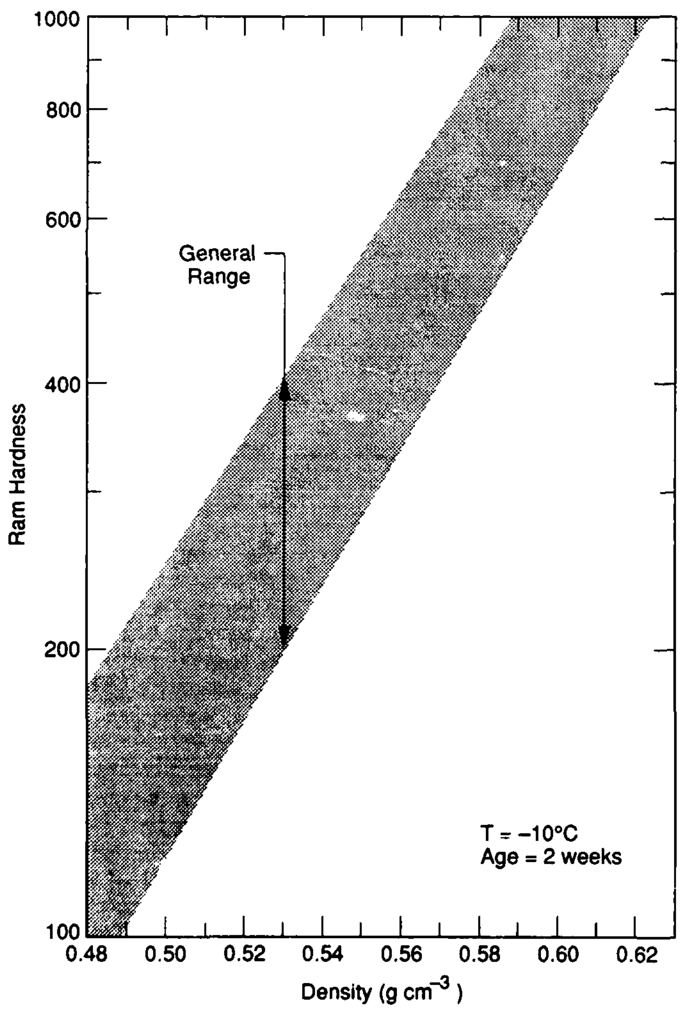


Figure 27. Ram hardness vs density for processed snow.

However, a power relationship (suggested by Russell-Head et al. 1983, 1984b) gives a slightly better fit, as shown by the curve in Figure 28, which can be expressed by

$$\sigma = 0.37\, R^{0.55}\,. \tag{4}$$

For a rough estimate using a simple, convenient expression, the relationship can be approximated by

$$\sigma(\text{kg cm}^{-2}) \approx 0.5\, \sqrt{R}$$

$$\sigma(\text{psi}) \approx 7\, \sqrt{R}$$

or $$\sigma(\text{kPa}) \approx 48\, \sqrt{R}\,. \tag{5}$$

Figure 29 shows the relationship between ram hardness and the NCEL shear strength (refer to Fig. 7), based on a limited amount of data (Abele 1968).

California Bearing Ratio vs snow density is shown in Figure 30. Since not only the CBR but also the density is on a logarithmic scale (which, for such a narrow range, is not greatly different from an arithmetic scale), the relationship can be approximated by

$$\text{CBR} = 250\, \rho^4 \tag{6}$$

where density ρ is in g cm^{-3}.

The CBR vs ram values are plotted in Figure 31. The relationship is expressed by

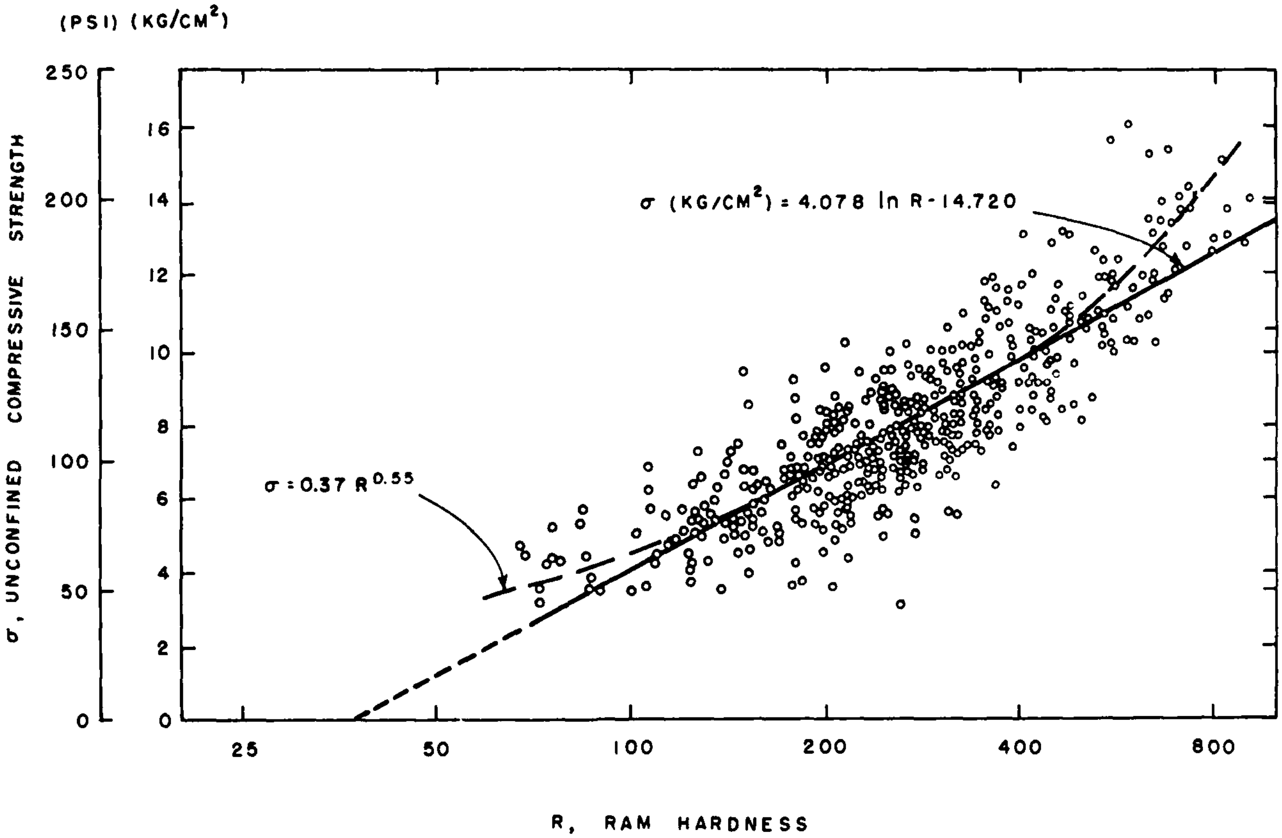


Figure 28. Unconfined compressive strength vs ram hardness (Abele 1963a).

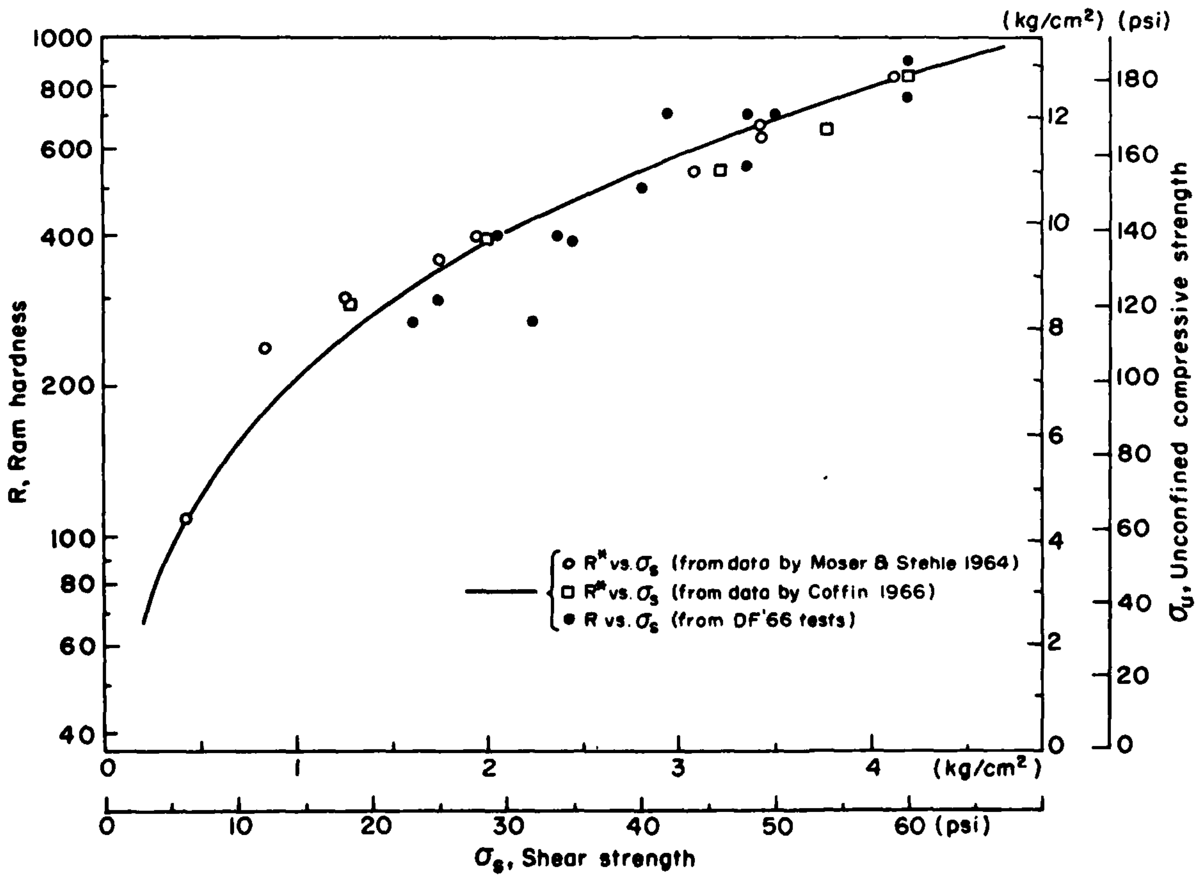


Figure 29. Ram hardness vs NCEL shear strength (Abele 1968).

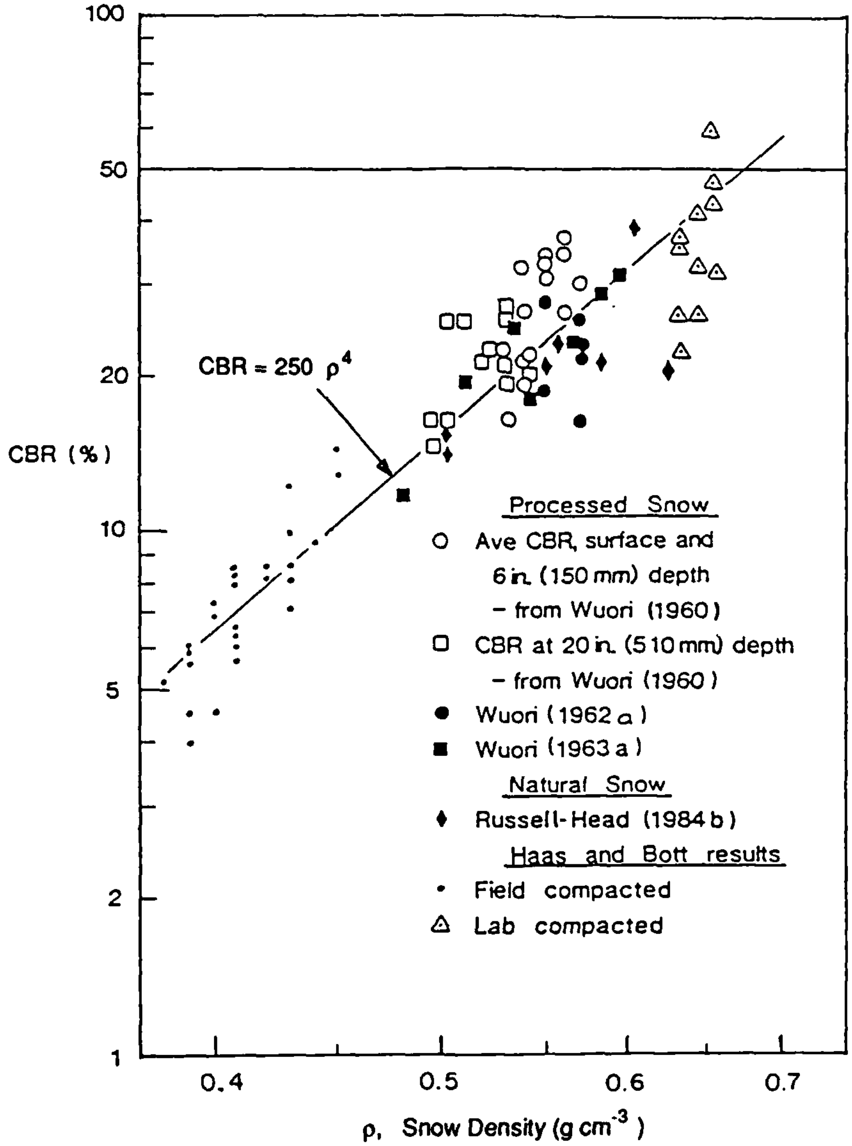


Figure 30. CBR vs density. (From Haas and Bott 1986.)

$$CBR = 1.44\ R^{0.48}\ (r = 0.78). \tag{7}$$

For a rough estimate of the CBR from ram hardness, the relationship can be approximated by

$$CBR \approx 1.25\ \sqrt{R}\ . \tag{8}$$

The relationship between the CBR and the Clegg CIV for soils (Clegg 1983) is

$$CBR = 0.07\ (CIV)^2. \tag{9}$$

The approximate relationships between the various strength and hardness indices are shown in Figure 32 (Abele 1988b).

To determine the relationship between the hardness values obtained with the 30° and 60° Rammsonde cones, data from Niedringhaus's (1965) study were used (Abele 1988a). The arithmetic plot, shown in Figure 33, resulted in the following relationship:

$$R_{60} = 1.56\ R_{30}. \tag{10}$$

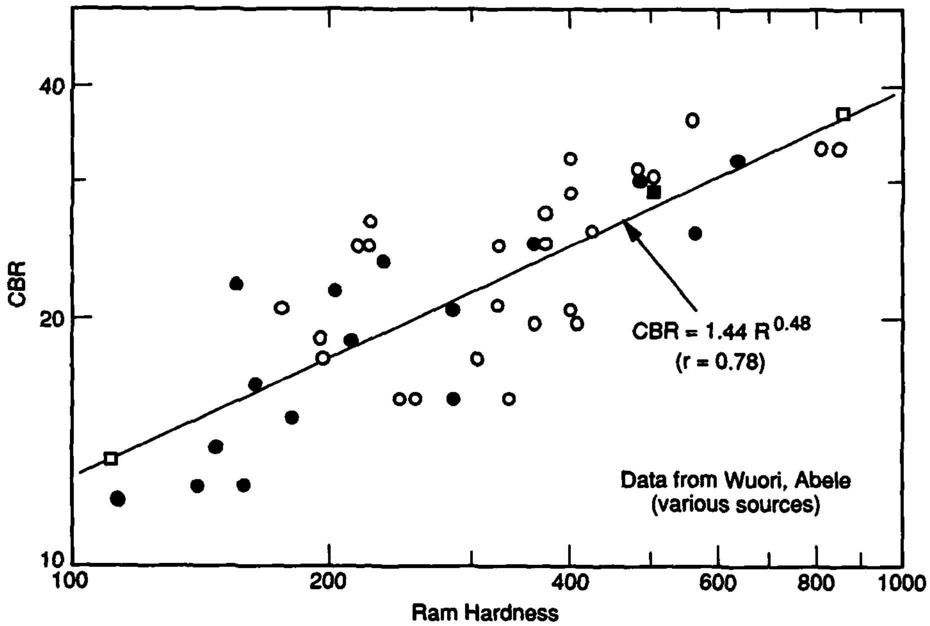


Figure 31. CBR vs ram hardness.

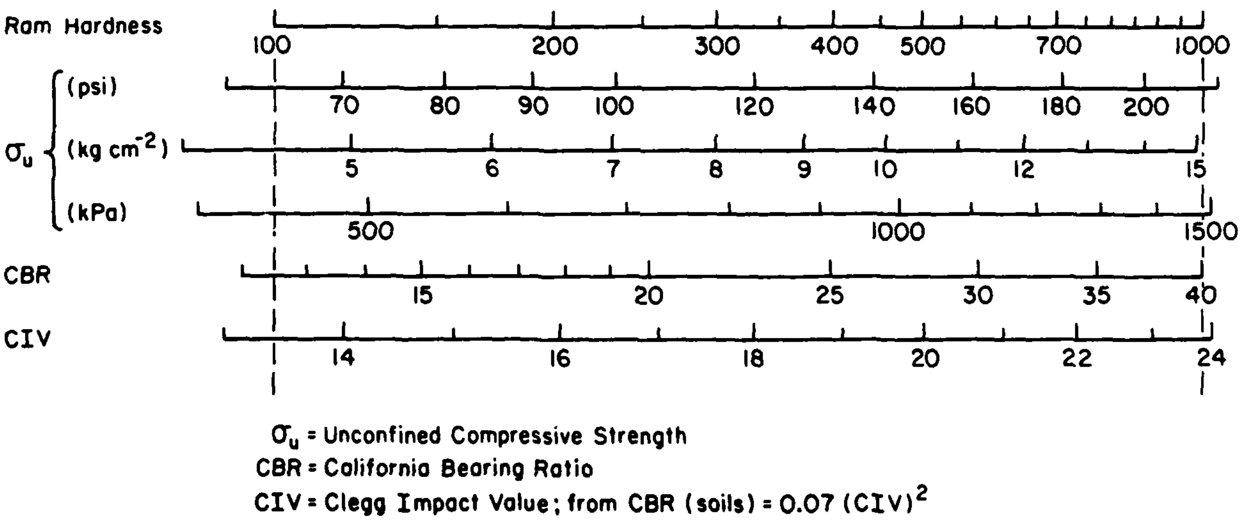


Figure 32. Interrelationship between various snow strength indices.

A log–log plot (Fig. 34) resulted in

$$R_{60} = 0.91 \; R_{30}^{1.1} \; . \qquad (11)$$

For practical purposes, to estimate the standard ram hardness value (60° cone), the hardness value obtained with the 30° cone can be multiplied by 1.5 for measurements obtained below a depth of 10 cm. For the 0- to 10-cm depths, the factor is approximately 2.

Behavior under load

The response of a snow surface when subjected to stress at a constant rate of penetration is illustrated in Figure 35. The pressure–sinkage relationship at first follows a relatively smooth line until an initial collapse occurs, which is followed by a series of repeated collapses, ultimately leading to complete destruction of the snow structure. The initial collapse point does not represent the bearing capacity of the snow; the maximum

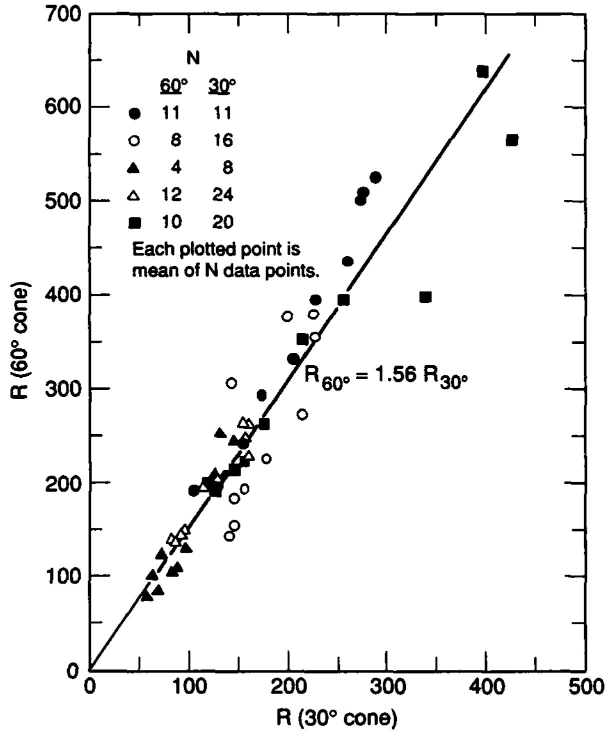


Figure 33. Arithmetic plot of the relationship between ram hardness values obtained with 30° and 60° cones. (Data from Niedringhaus 1965.)

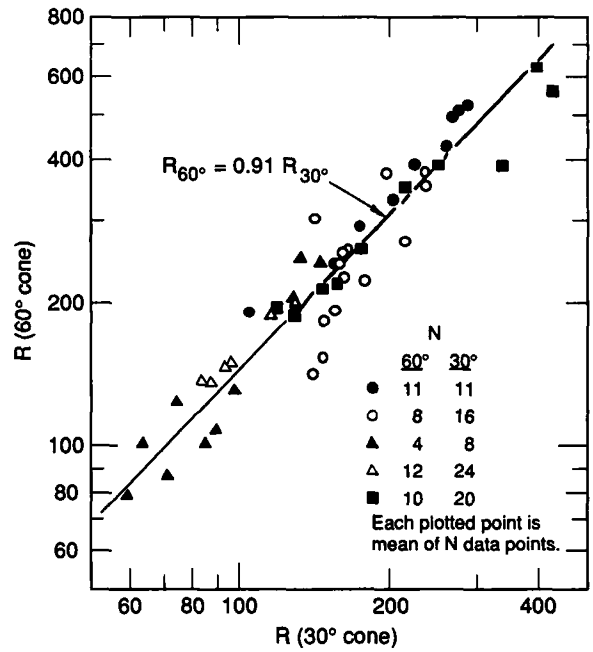


Figure 34. Log–log plot of the relationship between ram hardness values obtained with 30° and 60° cones. (Data from Niedringhaus 1965.)

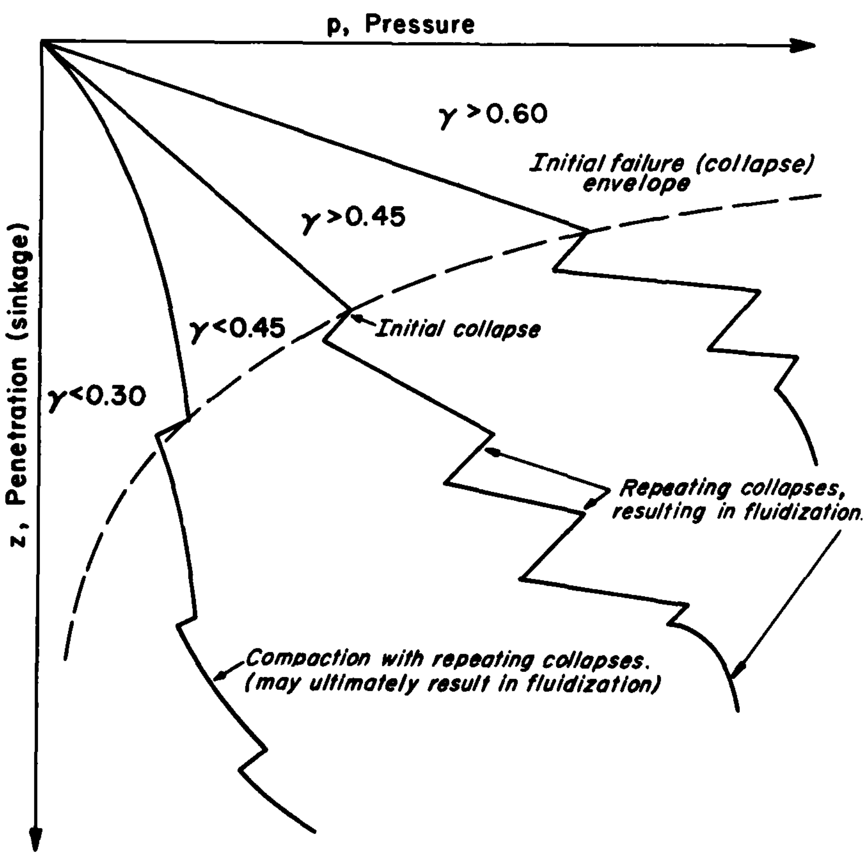


Figure 35. Response of snow to applied loads (Abele 1967).

strength is not reached until the snow has been subjected to significantly more deformation than indicated by the applied stress at the initial collapse.

The deformation (the bearing plate penetration into the snow surface) at the initial collapse decreases with an increase in snow density. Figure 36 shows pressure–sinkage relationships before the initial collapse for various snow densities at −12°C after age-hardening of at least 3 weeks (Abele 1967). If the snow density is plotted vs the bearing plate penetration at the initial collapse point, the relationship can be approximated by a straight line on a log–log plot for the density range of 0.3–0.6 g cm^{-3} (Fig. 37).

The progressive collapse characteristics of snow can also be observed during typical unconfined compressive strength tests (Fig. 38).

Typical examples of the response of high-density snow to a constant load are shown in Figure 39 as penetration vs time (Wuori 1957b, 1959). The load conditions simulate heavy aircraft wheel loads (parked

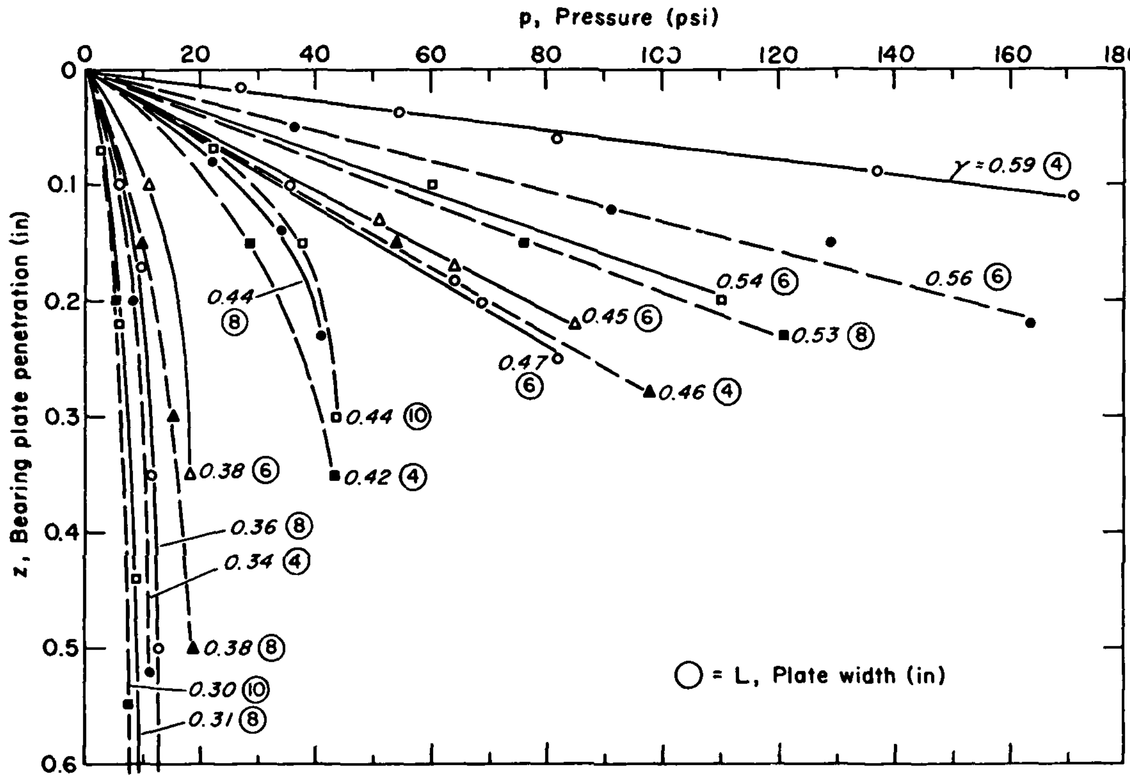


Figure 36. Bearing plate penetration vs pressure (Abele 1967).

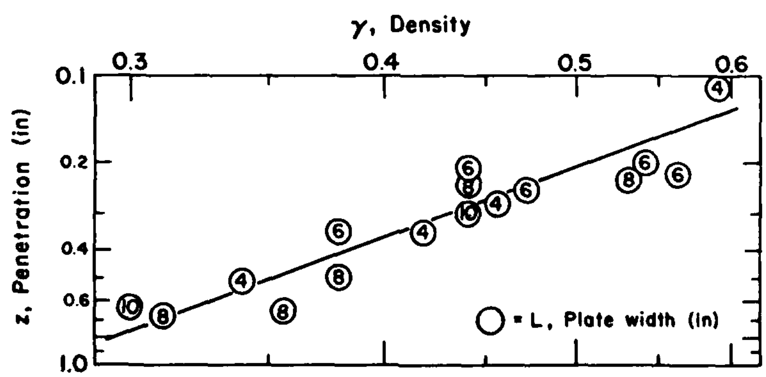


Figure 37. Bearing plate penetration at initial collapse vs density (Abele 1967).

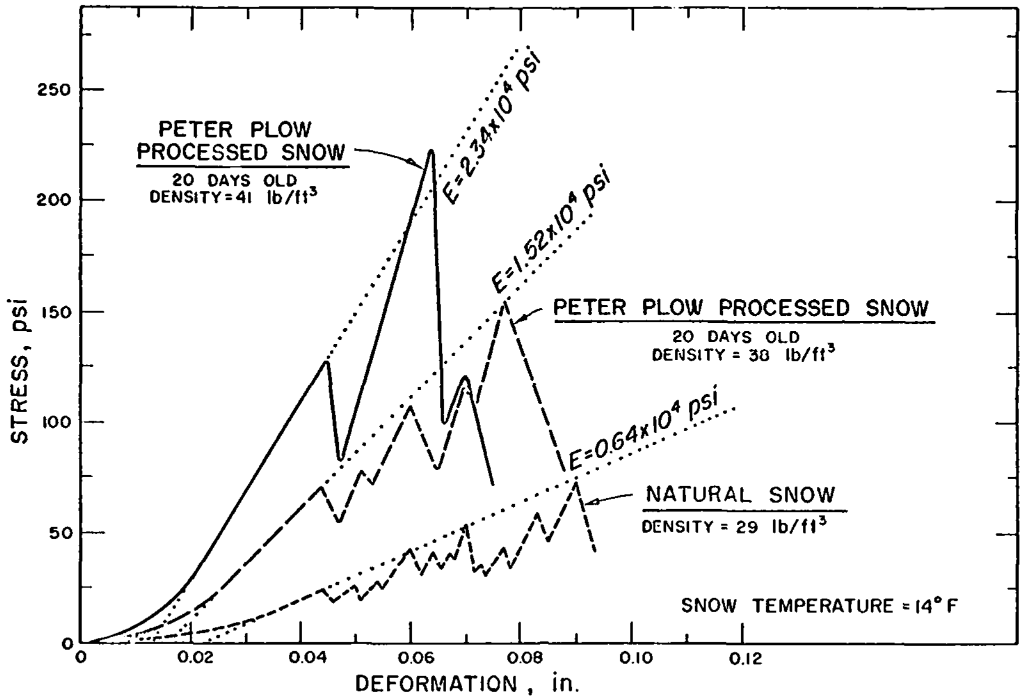


Figure 38. Progressive collapse of snow under load.

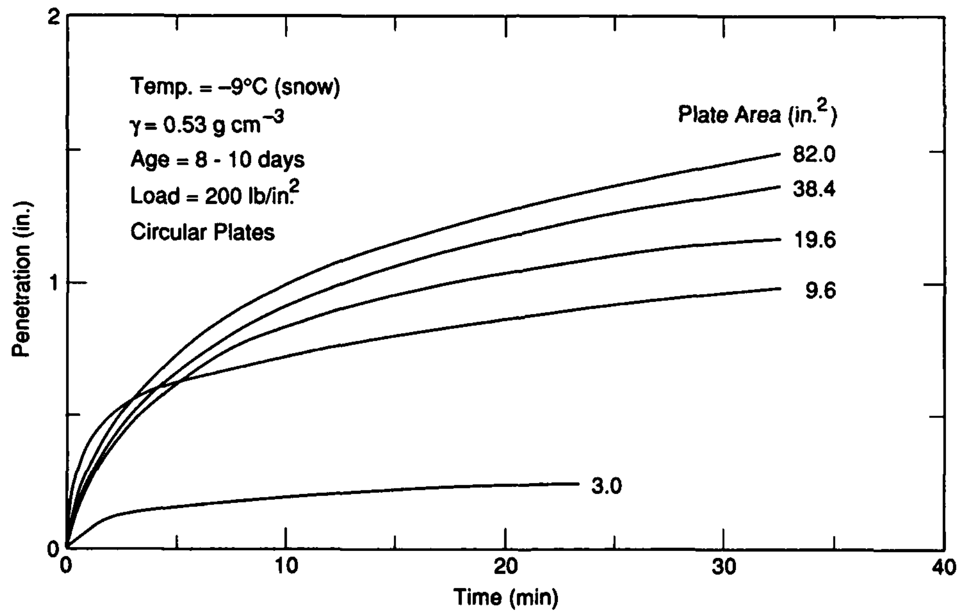


Figure 39. Penetration of bearing plates under a constant load vs time (Wuori 1957b).

condition) on a snow runway at temperatures of –7° to –10°C. In addition to temperature, the contact pressure and initial snow strength, which are the principal parameters influencing the rate of load penetration, the size of the loaded area also has an effect on the penetration rate. In general, for the same contact pressure, the penetration increases with an increase in the contact area. For example, if an aircraft landing-gear load of 5000 kg (11,000 lb) is supported by a single tire with a contact area of 500 cm^2 (a mean contact pressure of 10 kg cm^{-2}, or 142 lb $in.^{-2}$), that tire will sink somewhat more than would two smaller tires, each with a contact

area of only 250 cm^2 supporting the same 5000-kg load (the mean contact pressure of each tire is still 10 kg cm^{-2}).

Typical examples of the deformation of snow beneath a rigid plate and a high-pressure aircraft tire are shown in Figures 40 and 41, respectively (Wuori 1962a). The vertical deformation under the center of the plate and the tire are plotted vs depth in Figure 42.

The distribution of stress in snow under a loaded area has been difficult to determine experimentally, and a theoretical approach has not been satisfactory (Abele 1967). The result of one theoretical approach (Kondratyeva et al. 1945) is shown in Figure 43. However, this curve of pressure distribution vs depth has not been confirmed by experimental data.

A limited study on the stress distribution in snow under a rigid plate was conducted at the Naval Civil Engineering Laboratory (Stehle 1970). The results are shown on the right side in Figure 44. The data used in plotting the lines of equal stress by interpolation were obtained from stress gauges placed in the snow sample at various locations. On the left side of Figure 44, the theoretical curves from Boussinesq's analysis of stress distribution in soil are shown for comparison.

Figure 45 compares the theoretical and actual stress distribution in soils with the experimental and deduced (assuming stress is proportional to strain) stress distribution in snow (Wuori 1962a, 1975, Abele 1967, Stehle 1970). The depth scale is normalized in terms of the ratio of depth to the contact area radius. The snow characteristics and test conditions are also shown.

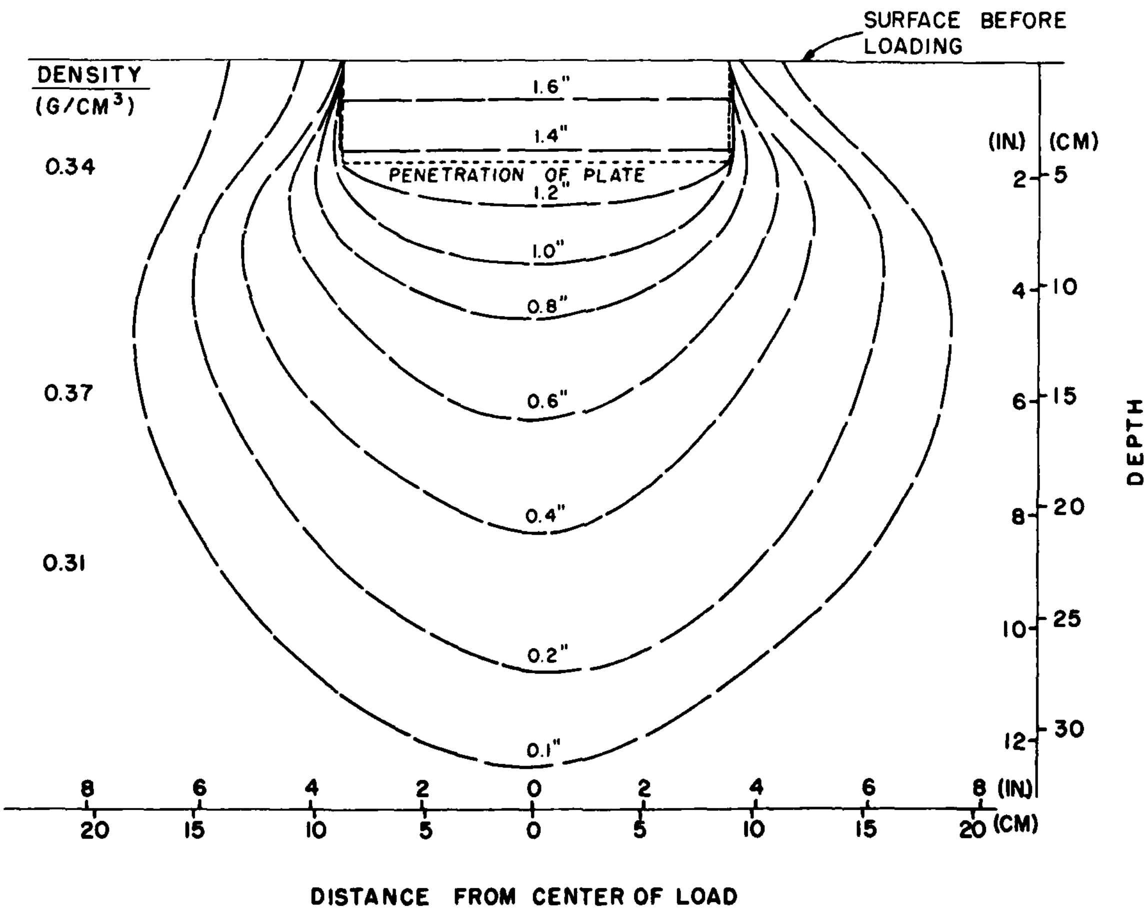


Figure 40. Deformation of snow beneath a rigid plate (Wuori 1962a). The lines show equal vertical displacement from the rigid circular plate load on Rolba snow age-hardened for 8 days. The plate diameter was 7 in.; the area was 38.4 in^2. The total load was 2000 lb and the unit load was 52 psi. The duration of the test was 15 minutes.

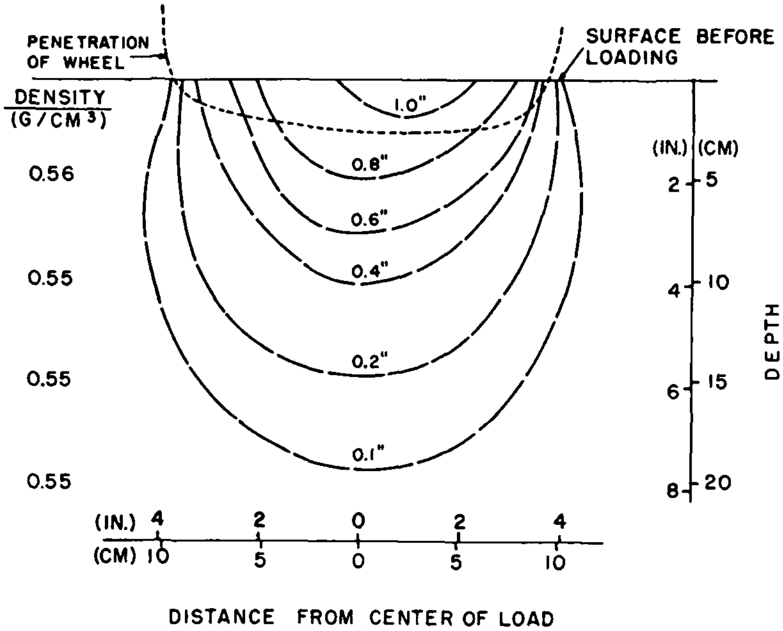


Figure 41. Deformation of snow beneath an aircraft tire (Wuori 1962a). The lines show equal vertical displacement from a surface wheel load on Peter snow age-hardened for 7 days. The F-86 wheel load was 10,410 lb; the inflation pressure was 152 psi. The snow temperature was -5°C. The duration of the test was 9 minutes.

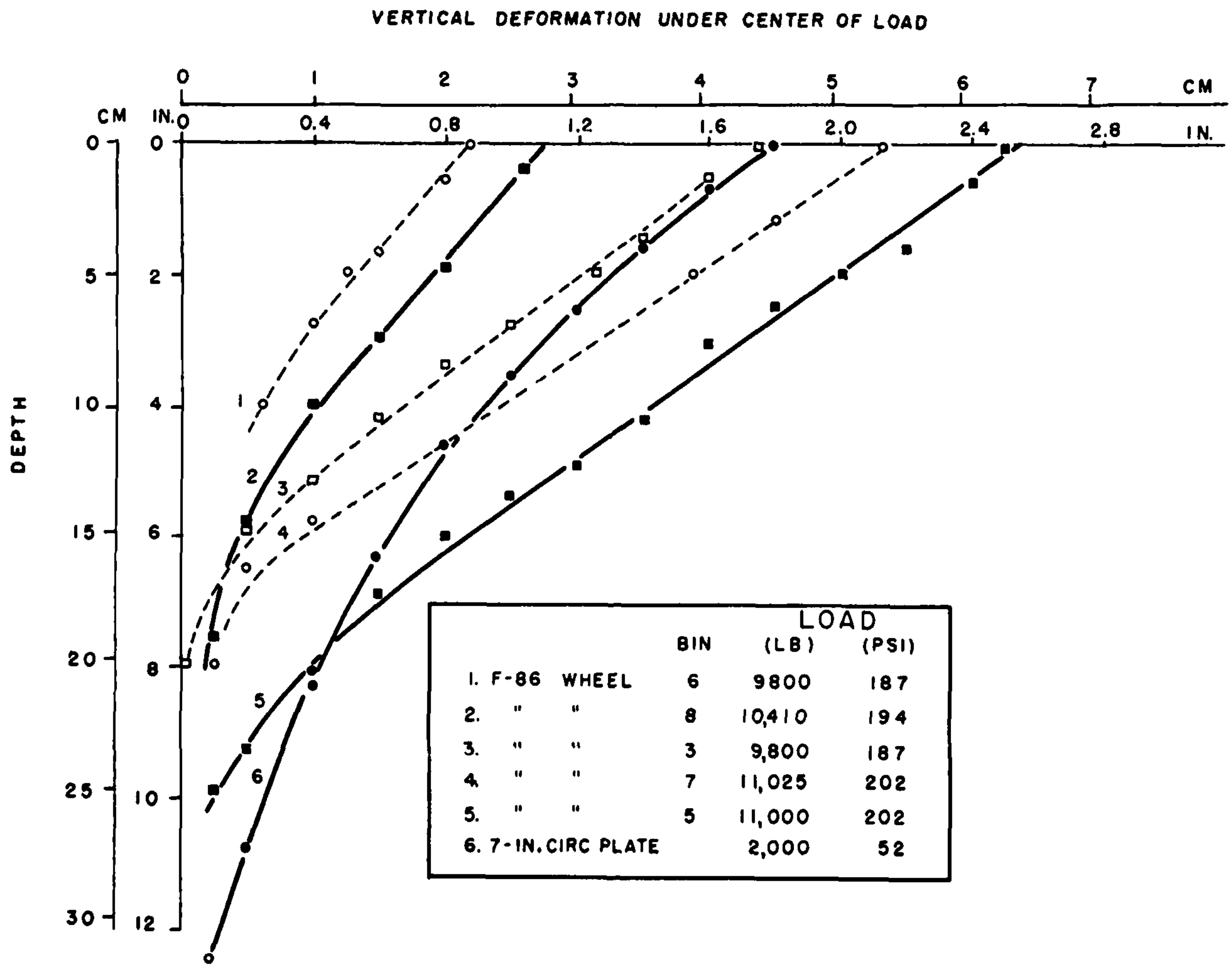


Figure 42. Deformation of snow beneath the center of a surface load (Wuori 1962a). The snow density was 0.55 gm/cm³ and the temperature was -6°C.

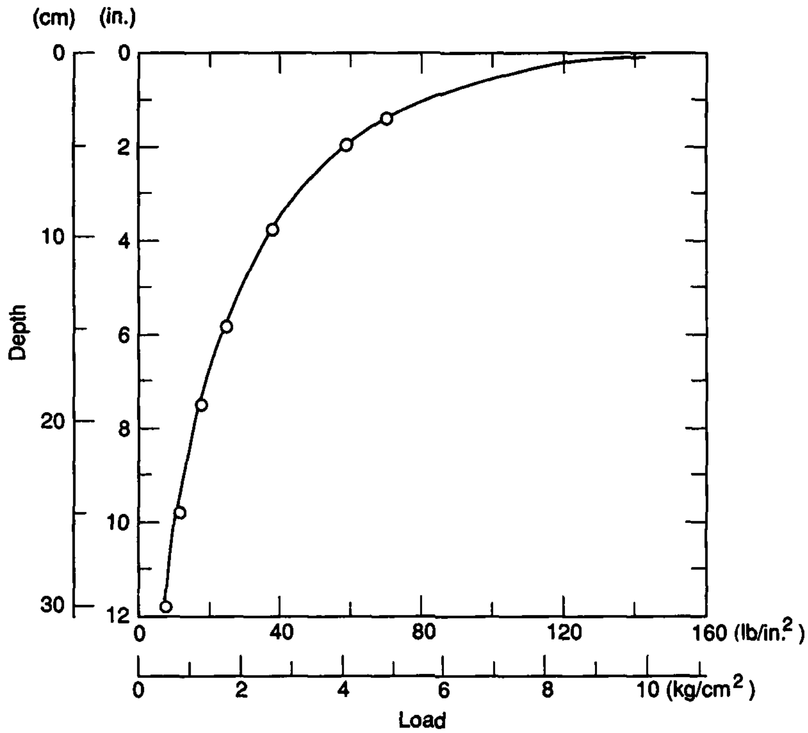


Figure 43. Profile of stress distribution below a load. (After Kondratyeva et al. 1945.)

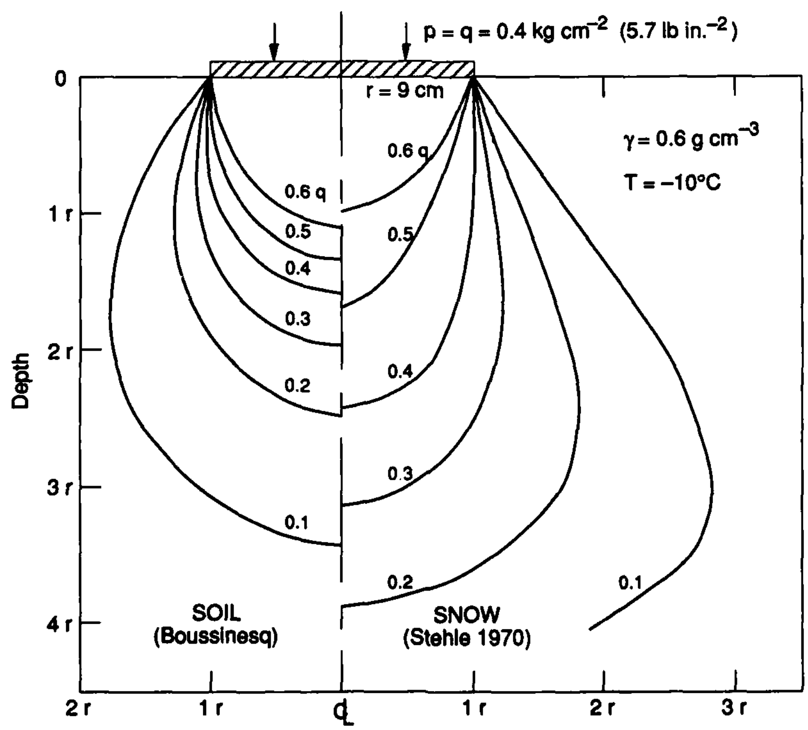
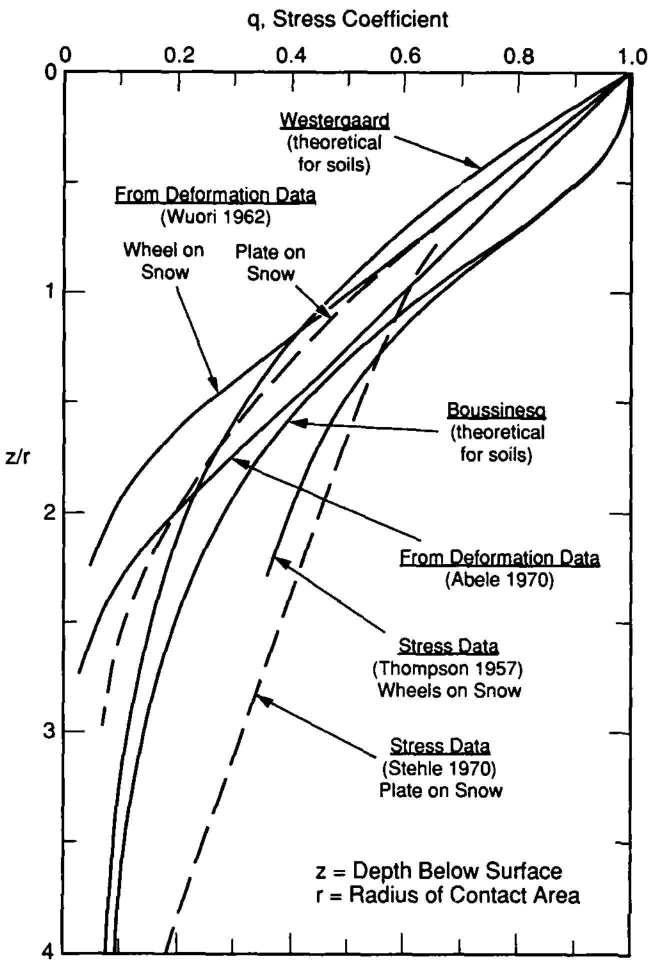


Figure 44. Stress distribution below a rigid plate. (After Stehle 1970.)



Test Conditions

Deformation data (Wouri 1962b)

Plate on snow: $r = 9$ *cm*
$p = 4$ *kg/cm*^{2}
snow $\gamma = 0.35$ *g/cm*^{3}
age = 8 days
$T = -5$°*C*
surface deformation = 4.5 cm

Wheel on snow: $r = 10$ *cm*
$p = 14$ *kg/cm*^{2}
snow $\gamma = 0.55$ *g/cm*^{3}
age = 7–13 days
$T = -5$ *to* -7°*C*
surface deformation = 2–6 cm

Deformation data (Abele 1970)

Plates on snow: $r = 5–10$ *cm*
$p = 5–12$ *kg/cm*^{2}
snow $\gamma = 0.45–0.6$ *g/cm*^{3}
age = 25–70 days
$T = -12$°*C*
surface deformation = 0.3–0.6 cm

Stress data (Thompson 1957)

Wheels on soil: $r = 10–14$ *cm*
$p = 2–4$ *kg/cm*^{2}

Stress data (Stehle 1970):

Plate on snow: $r = 9$ *cm*
$p \leq 0.4$ *kg/cm*^{2}
snow $\gamma = 0.6$ *g/cm*^{3}
age = 4 days
$T = -10$°*C*

Figure 45. Comparison of stress distribution data from various sources.

SNOW PAVEMENT CONSTRUCTION TECHNIQUES

Types of snow pavements

The characteristics of snow pavements, their preparation techniques and their subsequent use can vary significantly; however, there is no one established method for classifying the various types of snow pavements.

Common terms such as "runways," "roads" and "trails" may imply the type of use or type of traffic, but they do not necessarily indicate the required snow pavement characteristics. For example, a snow road for heavy truck traffic requires a substantially better pavement than that needed for a snow runway to be used by light aircraft or heavy aircraft on skis. That is, terms such as "snow road" or "snow runway" are not always useful descriptors of the pavement properties or the construction techniques. A "snow trail" usually implies a pavement suitable only for tracked or low-ground-pressure vehicles.

Adam's (1978b) classification of winter roads is shown in Table 1. Snow (and ice) roads are classified according to their method of construction, and winter trails are classified as either temporary (annual) or perennial. The method of construction and the material used is certainly a logical approach for a snow (or ice) road classification. However, we have to be careful about the terminology.

Because of the definition of "winter roads" (Table 1), this classification scheme does not automatically include perennial snow (or ice) roads in such areas as Antarctica and Greenland, although their construction procedures and pavement characteristics may be the same as those for temporary (annual) snow roads. The term "perennial winter trail" by itself, without the definition, may be misleading. Only the location is perennial; the snow pavement is only temporary (annual). Also, the term "perennial" conflicts with the definition of winter roads (annual).

Table 1. Classification of winter roads. (After Adam 1978b.)

Trail type	*Description*
Winter trails	
Temporary winter trail	A trail established for use during one winter season by a single pass of a tracked or wheeled vehicle using a blade if necessary to gain access. Seismic lines generally fall in this category. Temporary trails are not usually acceptable in permafrost regions since surface smoothness is often obtained by blading off the tops of hummocks.
Perennial winter trail	A trail established for use over several winter seasons along new or existing rights of way. Depressions are filled with snow in permafrost regions or with a mixture of mineral soil and snow in nonpermafrost regions. Drags or blades are used to fill depressions; this often leads to the "scalping" of hillocks or ridges and introduces mineral soil into the snow.
Snow roads	
Compacted snow road	A road built primarily with snow as a cut-and-fill material to establish some semblance of a constructed road grade. Compaction, the final step of construction, is accomplished by crawler tractor, drags or rollers.
Processed snow road	Similar in construction to a compacted snow road except that the snow is agitated or processed to reduce the size of the particles before compaction.
Ice-capped snow road	Either a compacted or processed snow road on which water has been sprayed to produce a bond between snow particles and give added stability to the roadway.
Artificial snow road	A compacted snow road built of artificial or manufactured snow hauled and end-dumped into place or manufactured on site. The road is shaped and compacted by crawler tractor.
Ice roads	
Solid ice road	A road built by sprinkling, spraying or hosing water directly on the ground to fill depressions and produce an ice surface of suitable thickness to support traffic.
Aggregate ice road	A road built of crushed ice (ice aggregate) hauled and end-dumped into place. Water is sprinkled, sprayed or hosed onto the surface to bond particles.
Winter road on ice	A road built on the surface of frozen lakes or rivers. This type of road is very common in some areas of Canada because the surface is naturally smooth, no clearing of trees is required, and overall road preparation is minimal.

A comprehensive classification of snow pavements can be developed from two approaches: based on the materials and construction methods used in the pavement, and based on the strength or traffic-supporting capacity of the pavement.

Classification by construction methods

For the construction of snow pavements, ingredients such as water and ice aggregate are occasionally used to reinforce the snow. Additives such as sawdust and wood chips have been used experimentally (Abele 1963c, Wuori 1963b), but materials of this type are not normally available in sufficient quantities locally to be considered for practical use.

The various possible combinations of the three principal pavement construction components (snow, water and ice aggregate) are shown in a Venn diagram in Figure 46 and described in Table 2.

Snow used for snow pavements is always compacted snow, although the degree of compaction may vary. Processed snow is a type of compacted snow, involving an additional activity (mechanical disaggregation) prior to compaction. (Processing itself results in considerable densification of the snow.) Artificial snow is a type of processed snow, the snow being manufactured from water.

Water can be applied to the snow pavement by spraying after compaction or by introducing heat during compaction or processing, resulting in a snow–ice mixture.

Ice aggregate or chipped ice can be mixed with processed snow to increase the pavement density, or a mixture of snow, water and ice aggregate can be used to produce a high-strength pavement.

Some combinations of these three components are not practical. A compacted (unprocessed) snow and ice aggregate mixture is not realistic, since the mixing

Table 2. Classification of snow pavements according to construction methods.

Symbol	*Composition/Process*	*Pavements type/Remarks*
S	Snow (unprocessed or processed, compacted)	Most common snow pavement
W	Water (applied in liquid form)	Solid ice pavement
W_h	Water introduced by applying heat	
I	Ice aggregate (crushed ice)	Not useful without water
SW	Snow–water mixture (water sprayed on snow surface)	High-strength pavement surface, ice-capped snow pavement
SW_h	Heat applied to snow during processing	High-strength pavement
SI	Snow–ice aggregate mixture	Not greatly beneficial without water (or heat)
SWI	Snow–water–ice aggregate mixture	Used to repair snow pavements, not tried as a pavement
SW_hI	Heat applied to snow–ice aggregate mixture	Not tried, but a practical procedure
WI	Water applied to ice aggregate	Aggregate ice road (used in Canada)
W_hI	Heat applied to ice aggregate	No data; not tried

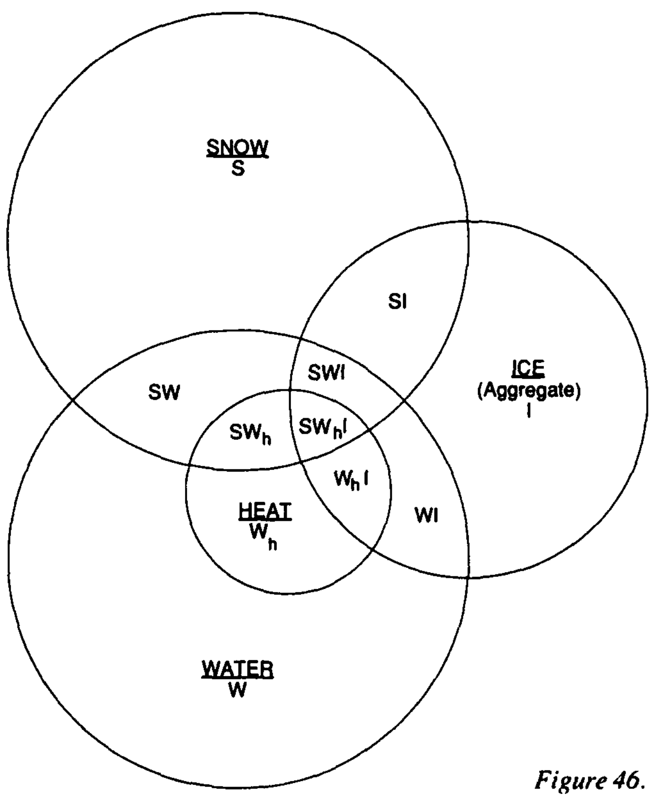


Figure 46. Possible combinations of snow pavement components.

action itself constitutes processing, and the mixture does not bond well unless water is also added. A mixture of water and ice aggregate constitutes an ice road and therefore cannot be classified as a snow road. The application of heat is practical only if done during processing; applying heat to a compacted snow surface is of little practical benefit for increasing the pavement strength. No field or test data are available on snow–water–ice aggregate mixtures, since the use of the latter component has been very limited.

Although most of the various possible combinations of snow, water and ice aggregate shown in Figure 46 have been tried in snow road preparation, actual construction has usually been limited to compacted and processed snow. The addition of water, either by sprinkling or by using heat, has been used only occasionally (Table 2).

Table 3. Classification of snow roads according to vehicle use. (After Johnson and Collins 1980.)

Type	*Use*	*Minimum snow thickness at density*	*Construction procedure*
I	Low ground pressure Rolligons Nodwells Crawler tractors Sleds 4WD trucks with wide tires	3 in. at 32 lb/ft^3 (0.51 g/cm^3)	Following refreeze of the active layer to 1 ft and accumulation of 6 in. of 18 lb/ft^3 snow, construction can begin. Rolligons and Nodwells will not require any trail preparation except clearing. Periodic use of a drag or roller will increase travel speed of Nodwells and Rolligons, remove ruts and create a surface suitable for occasional traffic with four-wheel-drive trucks with wide tires.
II	Light equipment Pickups Light trucks with axle loadings less than 8000 lb	3 in. at 38 lb/ft^3 (0.61 g/cm^3)	Treatment as above plus 8 passes with crawler-type tractors and drags or vibrating rollers with 1 week of sintering at 15°F, or 2 passes with drags or vibrating rollers with 2 weeks of age-hardening at 15°F, or 2 passes with crawler-type tractors and drags or vibrating rollers with addition of water and refreezing for immediate use.
III	Heavy trucks with axle loadings up to 20,000 lb	6 in. at 44 lb/ft^3 (0.70 g/cm^3)	Treatment as above plus an additional snow accumulation of 6 in. Additional compaction until the upper range of density is achieved, or addition of water until a ram hardness of 600–1000 is reached.
IV	Concentrated construction Trucks with axle loadings above 20,000 lb Locked-track turning of tracked vehicles	12 in. at 50 lb/ft^3 (0.80 g/cm^3)	Treatment as above plus an additional snow accumula- of 1 ft, and addition of water to saturate the upper 1 ft of snow.
V	*Steep slope construction* Longitudinal slopes exceeding 15% for distances greater than 200 ft Transverse sloped exceeding 5%		Special design required.

Therefore, the principal types of snow roads, based on their basic construction methods, can be classified into three groups:

- Compacted (compaction is accomplished with rollers, drags, vehicle tracks or wheels, etc.);
- Processed (processing is accomplished with a rotary snow miller or a pulvimixer to disaggregate and densify snow prior to final compaction); and
- Ice-reinforced (water is added by spraying or created by the application of heat either during or after processing or compaction).

The actual snow road construction methods and procedures are discussed later.

Classification by snow pavement strength requirements

A classification scheme based on the type of vehicles expected to use the snow pavement was developed by the Alyeska Pipeline Service Company (Johnson and Collins 1980) and is shown in Table 3. The required pavement properties are expressed in terms of snow density, and the construction procedure for achieving the required density for each type of pavement is described. Snow processing is not considered; the construction procedures are limited to various compaction techniques and the addition of water. Since this approach results in a pavement thinner than that obtained by depth processing with rotary snow millers, the required load-bearing capacity has to be achieved by very high snow density requirements. Ordinarily it is not possible to achieve snow densities above 0.6 g cm^{-3} without adding water, regardless of the compaction and processing methods.

Density is not always a reliable index of the snow pavement strength, since density by itself does not reflect the increase in strength with time (the period of age-hardening or sintering) or variations in strength due to

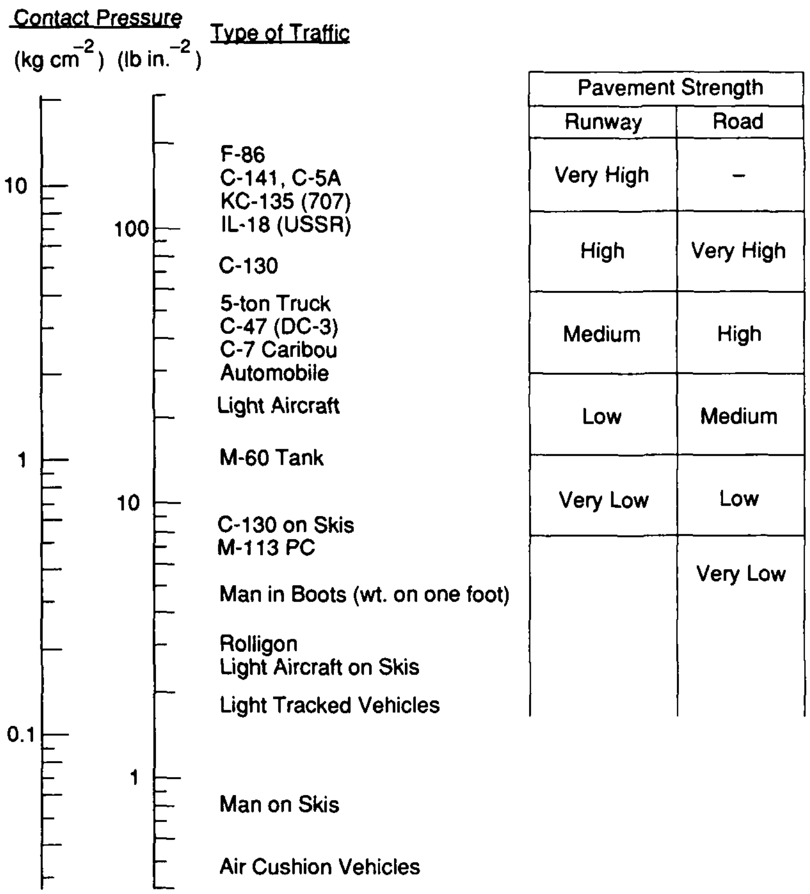


Figure 47. Classification of snow pavements according to wheel load contact pressures.

temperature. For example, a Type III pavement (Table 3) can be achieved as described in the table; however, it can also be achieved by processing the snow prior to compaction, resulting in a density of only 0.6 g cm^{-3}, and letting it age-harden for 3–4 weeks without adding any water.

At similar temperature and age-hardening conditions, a processed and compacted snow pavement will ordinarily exhibit higher strength than that which has been only compacted without the benefit of mechanical disaggregation. However, a snow pavement that has been well compacted (without processing) during favorable weather conditions (slightly below freezing) and later subjected to very low temperatures may result in a stronger pavement than that which has been processed and compacted during unfavorable weather conditions (low temperatures).

The construction procedures and the resulting snow density have a strong influence on the eventual strength properties of a snow pavement, but they do not guarantee a specific load-bearing capacity of the pavement, which can vary significantly with time and temperature.

A more practical snow pavement classification scheme can be developed, based on the actual strength (or some index of strength, other than density) of the pavement, which would indicate the capability of the pavement to resist the stress applied by a vehicle and would also reflect the influence of time and temperature on the snow strength. The stress or pressure applied by a wheel, track or ski is more critical than the gross load (a dump truck requires a stronger snow pavement than a C-130 aircraft on skis; a 200-lb man in boots requires a stronger pavement than a 200-ton air cushion vehicle). Therefore, for snow pavement design criteria, the stress-bearing capacity is a more important factor than the load-bearing capacity. (The effect of the load on the snow pavement design criteria is shown later in a nomograph.) Consequently snow pavements could be classified according to their stress-bearing capacity.

Figure 47 shows various types of vehicles and aircraft, arranged according to their ground contact pressure. The pavement classification scheme on the right side of the figure is purely arbitrary, ranging from "very low strength" to "very high strength," which covers a range of ground contact pressures of over two orders of magnitude. The construction procedures required to achieve the necessary pavement strength will vary depending on temperature conditions, thickness of snow cover, subbase properties, available age-hardening time, type and frequency of traffic, and expected contact pressures and loads. The pavement design criteria are discussed later.

Site selection

For snow roads, route selection will be influenced or dictated by the terrain topography, vegetation and snow cover characteristics. Frequently the route location is predetermined by existing or previously used routes or trails, and their suitability is well established. When selecting new routes, the primary objective is, of course, to minimize travel distance and construction cost. However, there are other conditions that have to be considered when selecting a route for a snow road.

The various terrain conditions and geographic characteristics that influence the selection of winter trail or snow road routes in northern Canada have been discussed in detail by Adam (1978b). The principal considerations for snow road route selection are listed below:

- Grades greater than 10% should be avoided, if possible.
- Sidehills should be avoided, if possible, to minimize potential problems caused by meltwater crossing the route.
- If sidehills cannot be avoided, north-facing slopes are usually preferable over south-facing slopes, since routes on the latter are subjected to more sunlight and will deteriorate before those on north-facing slopes.
- The lee side of hills may be preferable in cases where there is an insufficient amount of snow on the windward side; however, routes on the lee side may be subjected to more snowdrifting problems. The windward side is usually preferable if the amount of snow is sufficient.
- In forested areas, snow pavements shaded from the early afternoon sun will last longer in the spring than those exposed to the sun.
- Whenever possible, routes should be selected so that potential snowdrifting problems are minimized. The windward side of obstacles, high spots, bushes or shrubs, etc. is usually preferable, unless additional snow is required for the snow road construction and maintenance. In that case, the route should be located so that the route itself is not subjected to drifting, but the drift snow is conveniently available. (Some idea of the predominant wind direction is needed.)
- If the need for water (for making artificial snow) is anticipated, the route should be located near water sources.
- Low, wet areas are usually more level than high, dry areas and usually require less clearing and grading.
- When water bodies must be crossed, the suitability of the land-to-ice and ice-to-land transition areas have to be considered during the route layout.
- In permafrost areas, routes should be located where a sufficient amount of snow is already available, can be collected with snow fences, or can be hauled in or manufactured, and where grading and the construction process will not remove or harm the vegetation cover. It is very important that the surface organic layer in permafrost areas is not disturbed and the thermal regime not altered. The environmental protection considerations during site selection are discussed in detail by Adam (1978b).

Site selection for runways naturally involves more critical criteria than those for trails or roads, primarily because of the surface smoothness requirements and the size of the area involved (Clark et al. 1973). Areas with little or no vegetation are preferable. The site must be level, except for minor surface roughness. Under no circumstances should it contain ditches more than 0.5 m deep. The slope must not exceed that specified for airfield runways. The site should be clear of trees or other vegetation more than about 1 m high. In permafrost areas, care should be taken not to remove vegetation, which might cause degradation of the underlying permafrost in subsequent years. The site must be clear of natural or man-made vertical obstructions that would pose a hazard to safe landings and takeoffs. And, it must be sufficiently large to permit construction of a runway long enough to accommodate the aircraft that will use it.

The runway should be oriented so that the long axis is parallel to the prevailing wind direction. However, some consideration should also be given to storm wind direction, which can be at an angle to the prevailing wind. It is not desirable to have any protruding features such as surface relief, trees or shrubs close to and on the windward side of the runway, since these can cause potential drifting problems. If meteorological data for the area are not available, some idea of wind directions can be obtained by observing snowdrift patterns. (It may sometimes be difficult to distinguish snow surface features caused by storm winds from those caused by the prevailing winds.) Layout plans should include provisions for aircraft parking and unloading areas large enough to accommodate the maximum anticipated aircraft utilization.

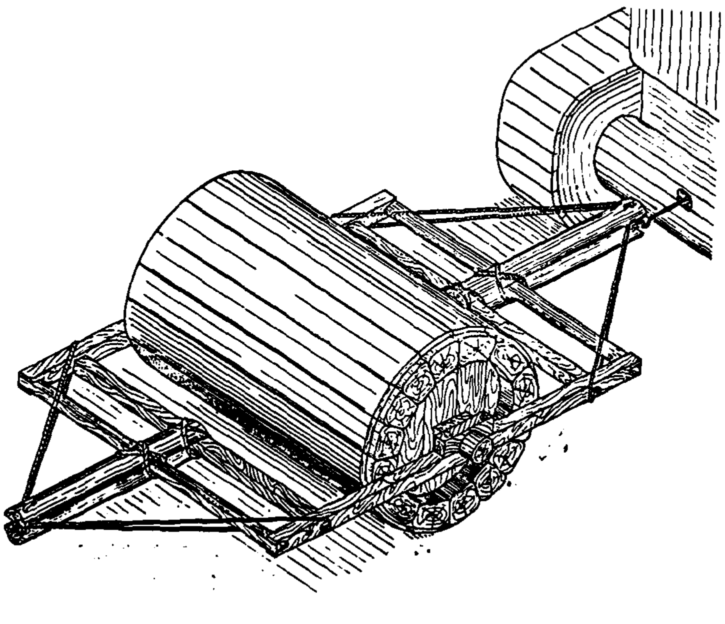


Figure 48. Improvised snow roller.

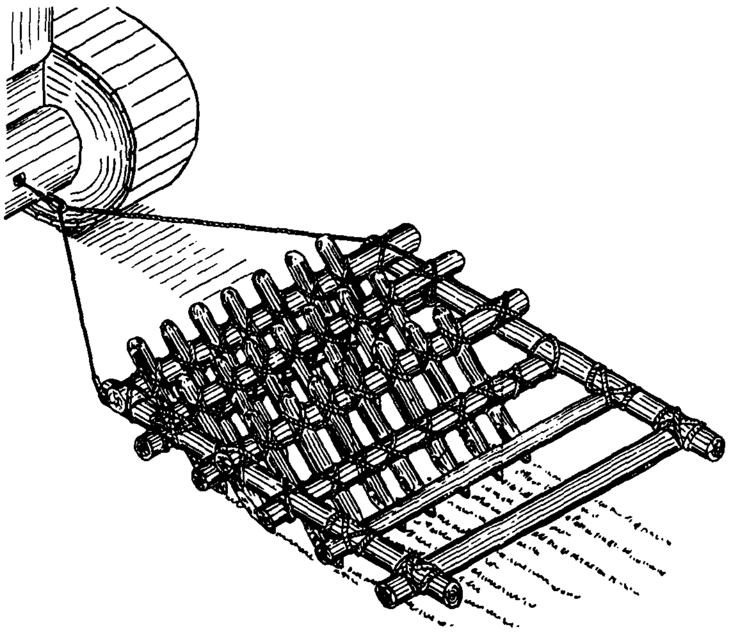


Figure 49. Improvised snow harrow.

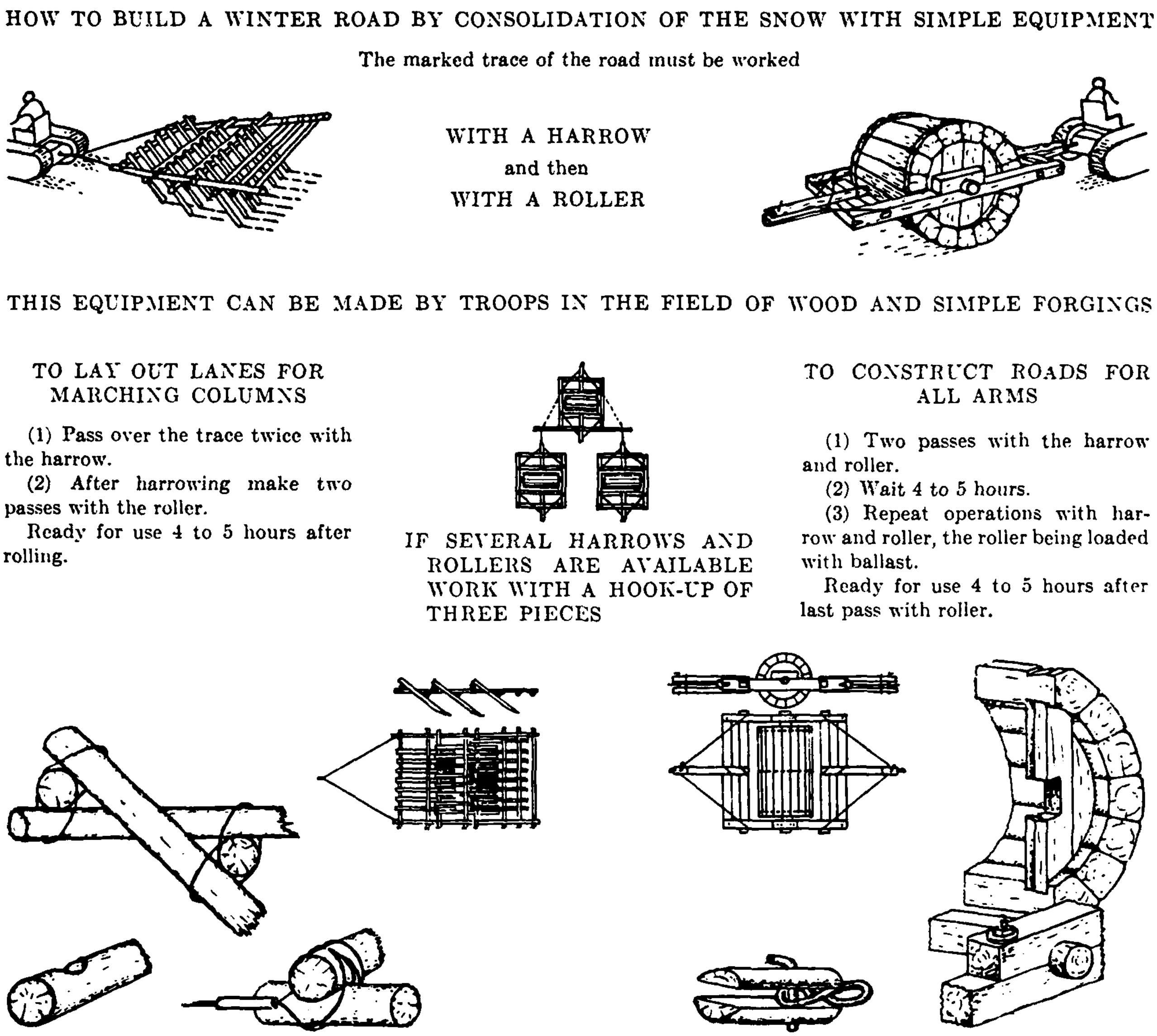
Expedient snow pavement construction

Basic equipment

The basic method used by the northern countries for improving the trafficability of snow-covered terrain during the winter logging operations has been and still is compaction with rollers and various types of drags. A typical improvised snow roller is shown in Figure 48.

Before the development and use of mechanized rotary snow mixers, improvised harrows (Fig. 49) and tillers were used for depth processing. Figure 50 illustrates the equipment and procedures used by the USSR. military for expedient snow trail and road preparation before and during World War II (Kragelskii 1945b).

The increases in density and hardness of a natural snow layer compacted with a wooden roller is shown in Figures 51 and 52 (Kragelskii 1945c, Kragelskii and Shakhov



Instruction Plate, Engineer Committee, Red Army.

Figure 50. Improvised snow road construction equipment used by Soviet combat troops in World War II (Kragelskii 1945b).

1945). Most of the density increase in the undisturbed snow was achieved after only two passes with the roller; additional rolling (eight more passes) resulted in relatively little further densification (Fig. 51). However, the apparently minor increase in density achieved with the additional roller passes resulted, after 12 hours of age-hardening, in a snow hardness increase that was approximately proportional to the number of roller passes (Fig. 52). (The hardness values were obtained with the 2.05-cm-diameter spherical head plunger; refer to Fig. 12.)

Figure 53 illustrates the effect of temperature during compaction with a heavy, curved-bottom float (Kragelskii 1945c). At –3.5°, compaction of a snow cover with a density of 0.2 g cm^{-3} resulted in an approximately 50% more densification than compaction at –15°C. At –3.5°C, one pass with the float increased the snow density from 0.2 to 0.43 g cm^{-3}, while at –15°C, 10 passes with the float were required to produce a density of 0.43 g cm^{-3}.

Figure 53 also shows the benefit of a time interval between consecutive compaction passes (refer also to Figure 51). The first three compaction passes, with a 4-hour interval between each pass, achieved as much densification as that achieved with six to ten consecutive passes without any time intervals.

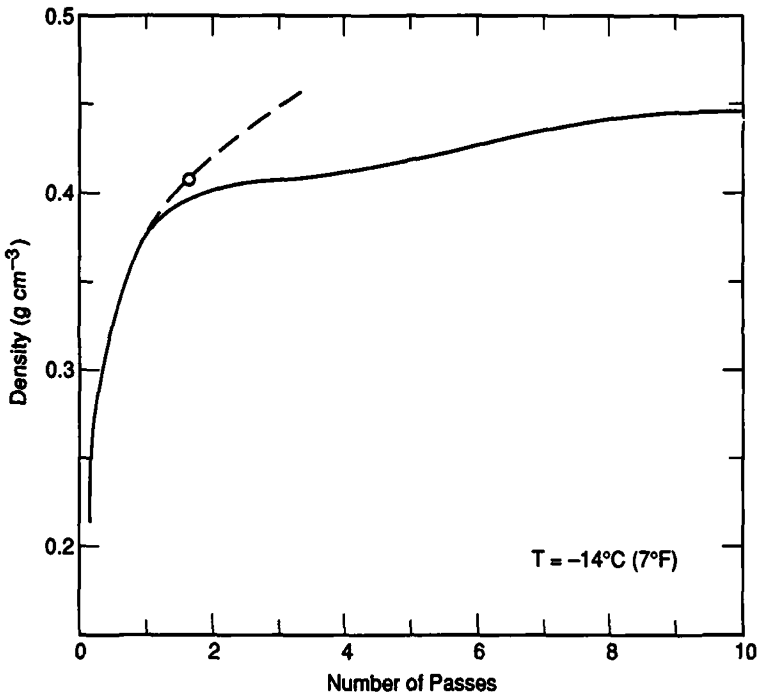


Figure 51. Snow density vs number of roller passes. (After Kragelskii 1945c.)

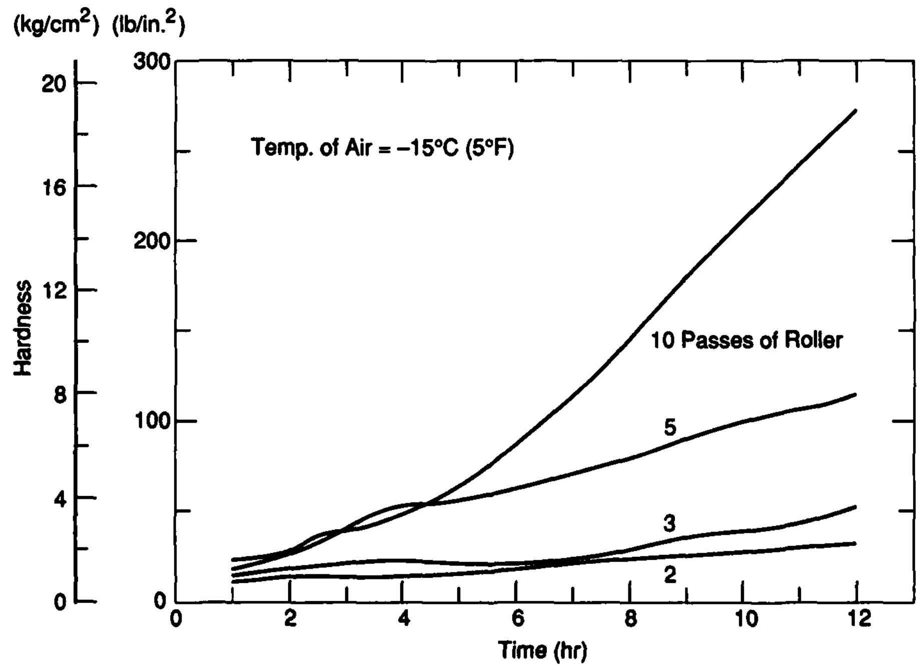


Figure 52. Snow hardness vs time for roller-compacted snow. (After Kragelskii and Shakhov 1945.)

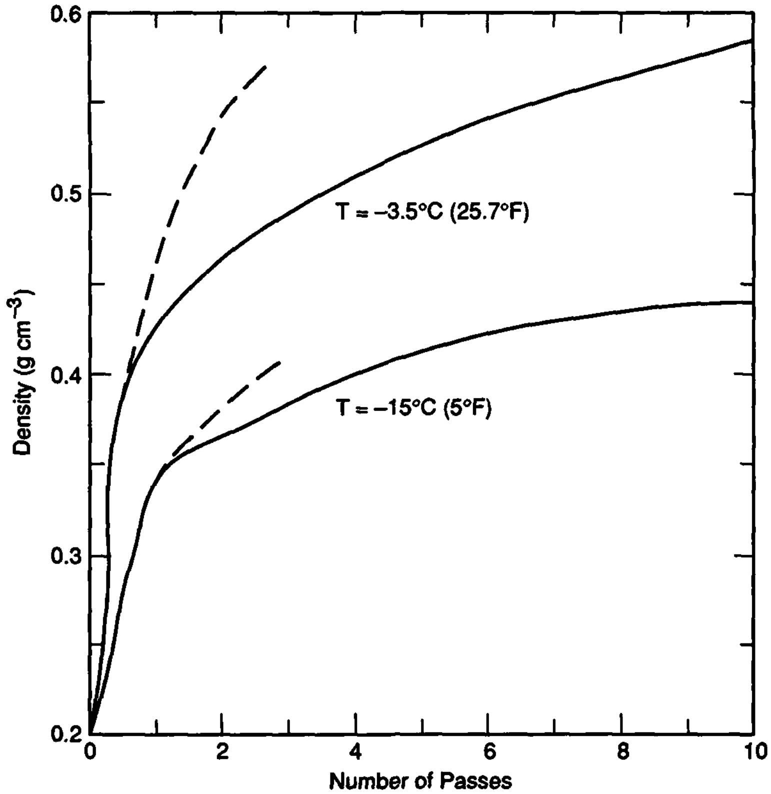


Figure 53. Snow density vs number of heavy float passes. (After Kragelskii 1945c.)

Expedient snow processing, compaction and leveling equipment can be constructed and improvised from various available materials (Clark et al. 1973). A peg-tooth A-frame harrow with metal pegs is illustrated in Figure 54. Corrugated culvert pipe can be used for constructing a roller, as shown in Figure 55. Leveling drags can be constructed from lumber (Fig. 56) or from fuel drums (Fig. 57). Figure 58 shows two types of drags used in Canada (Adam 1978b).

A typical expedient snow pavement construction procedure is shown in Figure 59. Although the specific operations in the construction process and the extent of their use (number of compaction and leveling passes, for example) may vary, depending on the terrain, snow and temperature conditions and the type of equipment available, a general sequence of operations has been developed based on experience and test results. The principal steps in the snow pavement preparation procedure are discussed below.

Initial site preparation

Unless open areas, such as perennial snowfields, tundra regions, frozen waterways, or existing or previously prepared routes, are used for snow roads, clearing of the right-of-way may be required, which should be done before any significant snow accumulation. Low surface vegetation can be packed down with low-ground-pressure vehicles. For tree and shrub removal and for surface leveling in non-permafrost areas, bulldozers are required.

Runway sites usually require more extensive terrain surface leveling and vegetation removal than road sites. All unnecessary traffic, especially with high-ground-pressure vehicles, should be avoided in the cleared area to prevent rutting of the terrain and disturbing and contaminating the snow cover prior to the snow pavement construction process.

Incremental compaction

If snow compaction equipment is available during the initial snowfall season, incremental compaction of each snowfall is preferable to disaggregation and compaction of a thick snow layer all at once. Compaction of thin layers produces a snow pavement with a more uniform strength profile. If this procedure can be continued throughout the winter season, no disaggregation or processing is required. Usually, however, this is not the case; snow pavement construction is ordinarily a one-time operation after sufficient snow has accumulated.

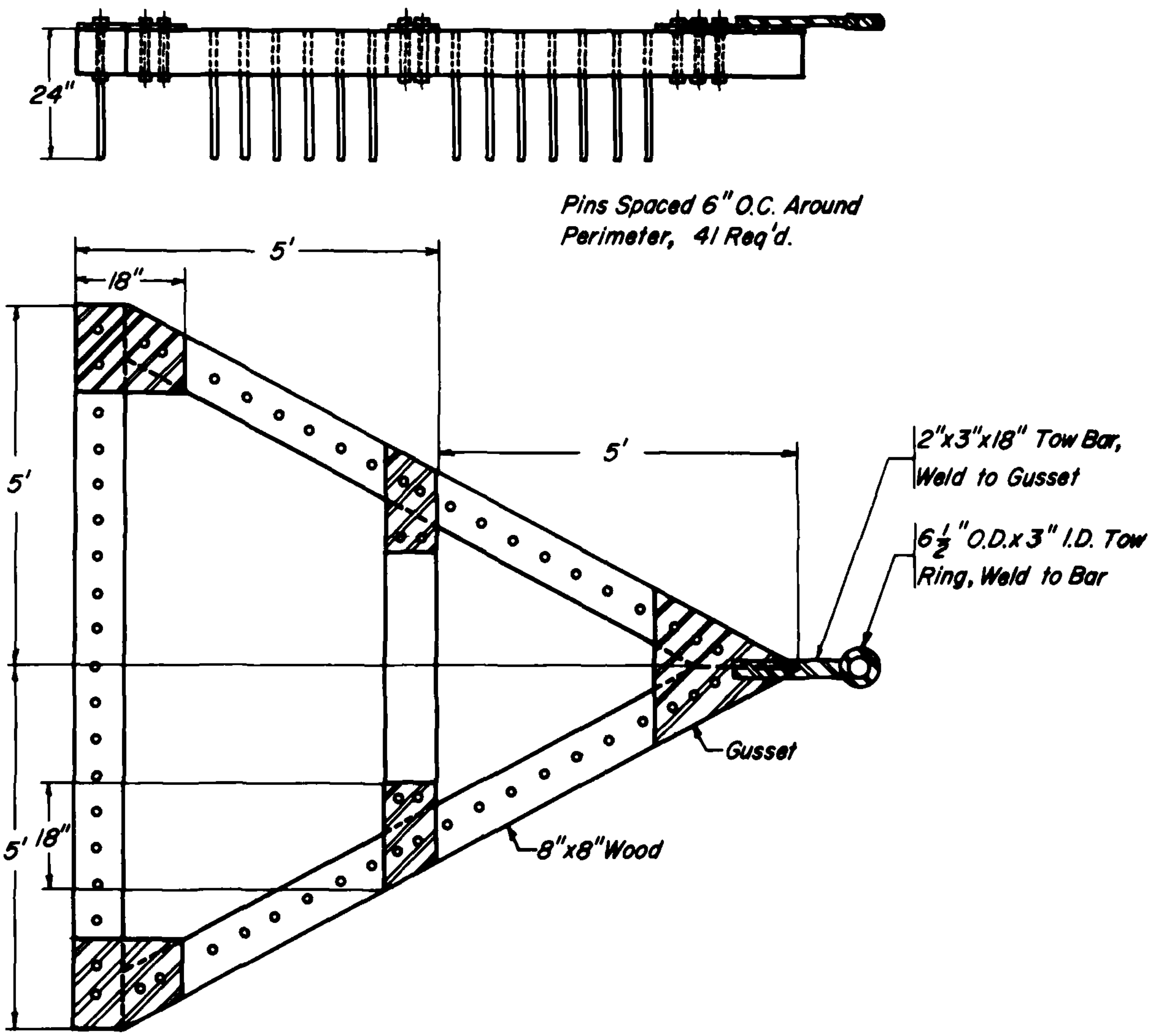


Figure 54. Peg-tooth A-frame harrow.

Initial leveling and precompaction

The snow surface should be relatively level before compaction is started. Leveling of the natural snow surface is usually needed, especially for a runway pavement. It is also beneficial to precompact deep, soft snow prior to disaggregation. Any leveling activity automatically results also in compaction. Low-ground-pressure, wide-track vehicles are especially suitable for precompaction. The snow surface should be sufficiently dense to limit vehicle track sinkage to less than 15 cm during the subsequent disaggregation. Rollers and drags can be used for the precompaction and leveling operations.

When preparing a snow runway site for disaggregation, equipment starting, stopping and turning should be done beyond the ends of the runway.

Figure 60 shows the snow density profile of the natural snow and the snow runway of the South Pole in 1965. The runway surface was prepared by periodic compaction with a roller, tractor tracks and a drag without disaggregation. For this type of snow and these temperatures (–35° to –45°C), the effectiveness of compaction extended to a depth of approximately 40 cm. The runway is used by ski-equipped C-130 aircraft. The pavement would not support C-130 aircraft on wheels (Abele et al. 1966).

Disaggregation

Since the effects of compaction alone are usually too limited in depth to provide a sufficiently thick snow pavement, some method of disaggregation (depth processing) may be required if the snow thickness exceeds

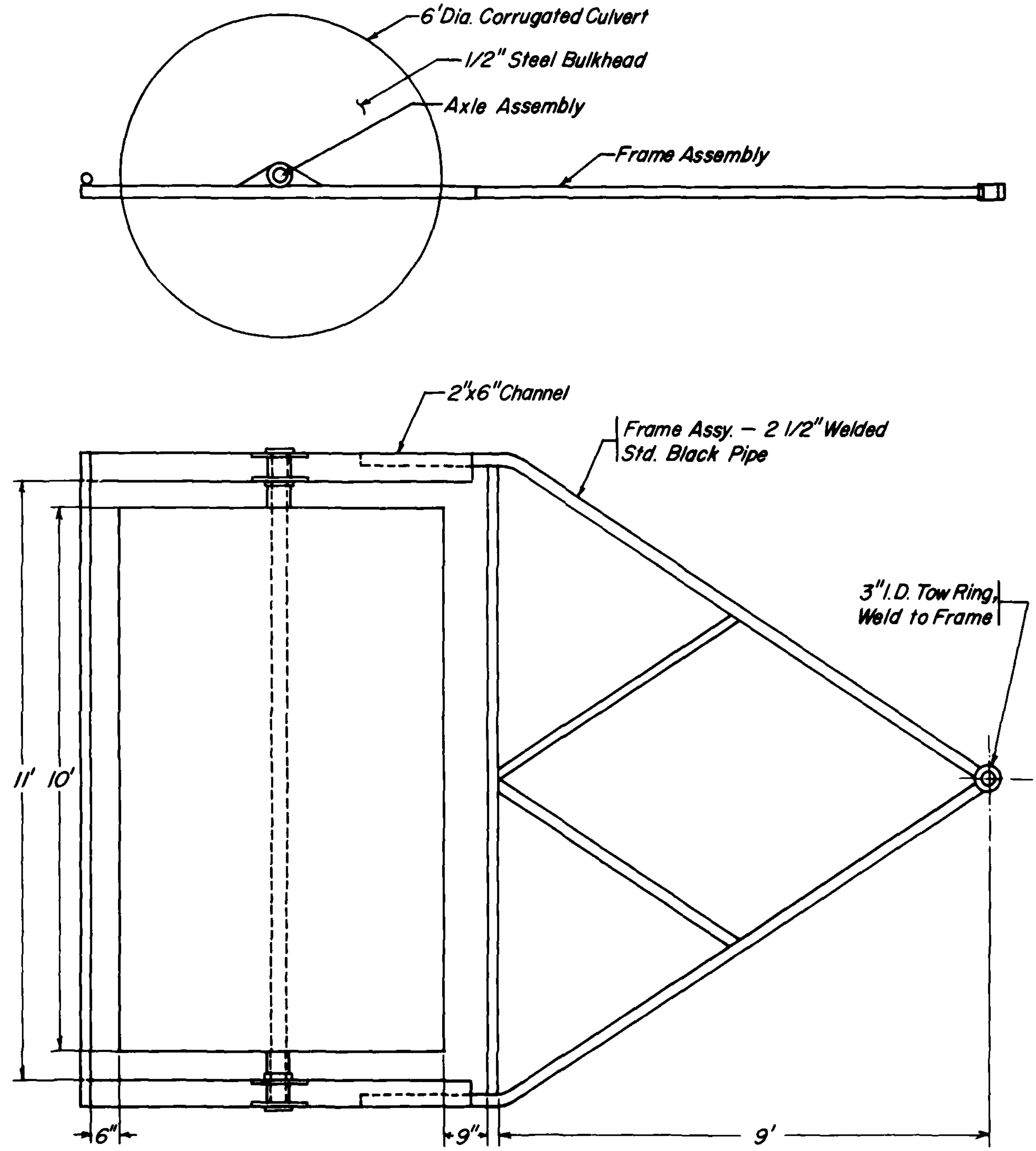


Figure 55. Corrugated roller.

30 cm. Improvised harrows, such as the peg-tooth A-frame type shown in Figure 54, which can be fabricated in the field, can be used for disaggregation.

More effective disaggregation will result from repeated passes with the harrow. Towing several harrows in tandem with a tractor is a preferable arrangement, since neither a time interval nor compaction with the tractor tracks between stages of the disaggregation processes is desirable. Ballasting of the harrows is not normally necessary except when the surface crust is unusually hard.

If either initial compaction or leveling of the snow has been necessary, some degree of age-hardening already has occurred due to this disturbance of the snow layer, so the disaggregation process should be performed as soon as possible (within hours), before the age-hardening process becomes too advanced and limits the harrow action.

Leveling

For maximum effectiveness, compaction should be performed immediately after disaggregation, and any required leveling should be performed prior to or during compaction. If possible, it is desirable to tow a smooth skid behind the last harrow (or during the last harrow pass), which also will produce some immediate compaction. If the surface after disaggregation is not sufficiently level, backblading with a bulldozer may be used, which will provide not only the leveling but also some compaction. For backblading operations, a hydraulically operated blade is preferable to a cable-operated blade. The snow pavement will be stronger and more uniform if leveling and grading can be held to a minimum after compaction is completed.

Compaction

The main compaction is accomplished with successive passes by rollers, with increased weight during each successive coverage. If ballast (dry crushed stone, gravel or sand inside the roller) is not available, the weight of

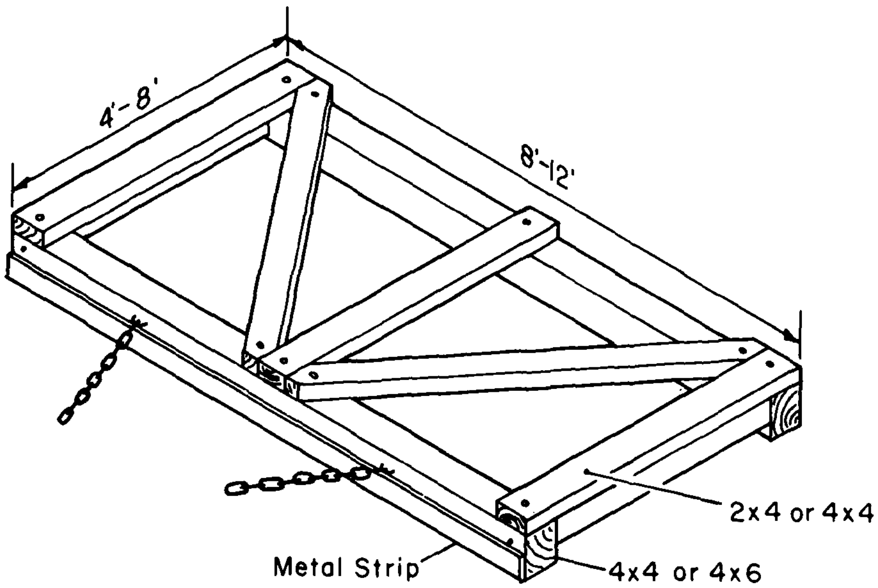


Figure 56. Improvised leveling drag.

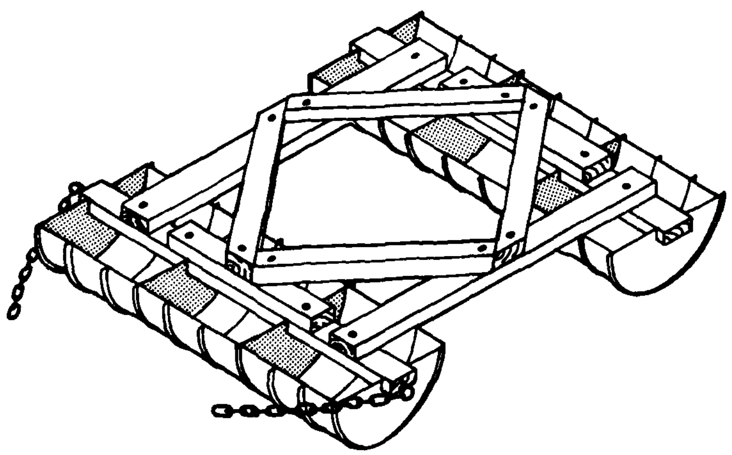


Figure 57. Improvised fuel drum drag.

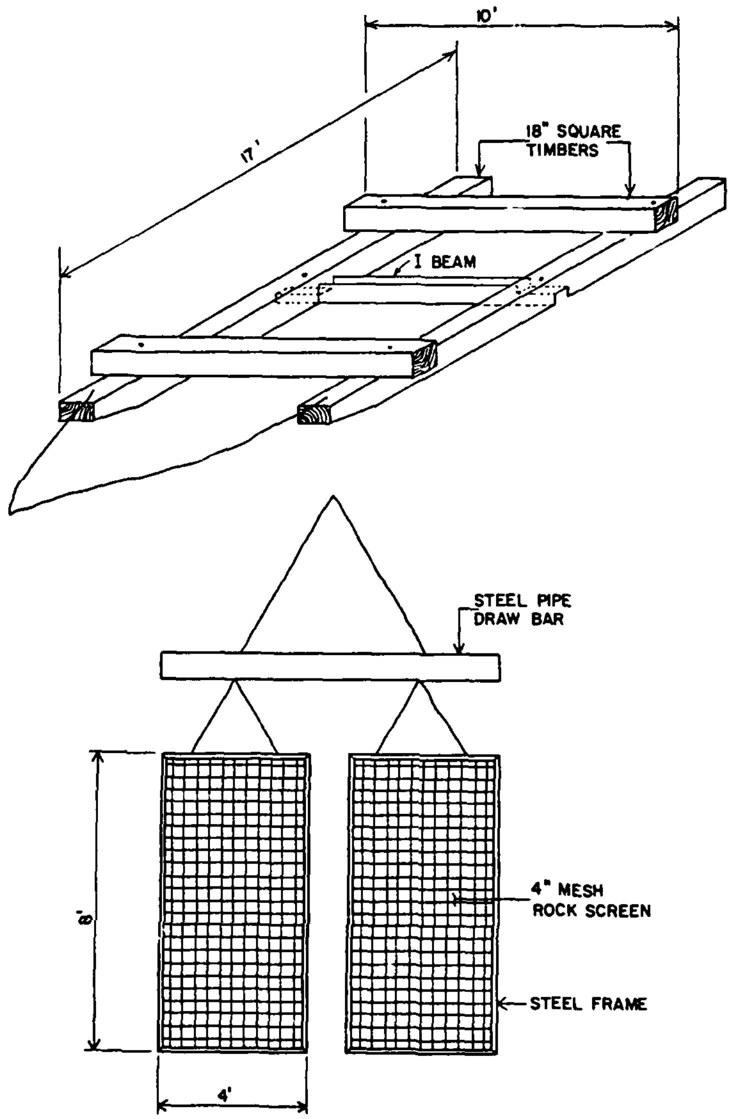


Figure 58. Drags used in Canada (Adam 1978b).

the roller can be increased by lashing metal or concrete beams or slabs to the towing bars. A method for ballasting should be considered when the roller is fabricated. If external ballast is to be used, the material used for construction of the roller should be considerably stronger than that shown in Figure 55.

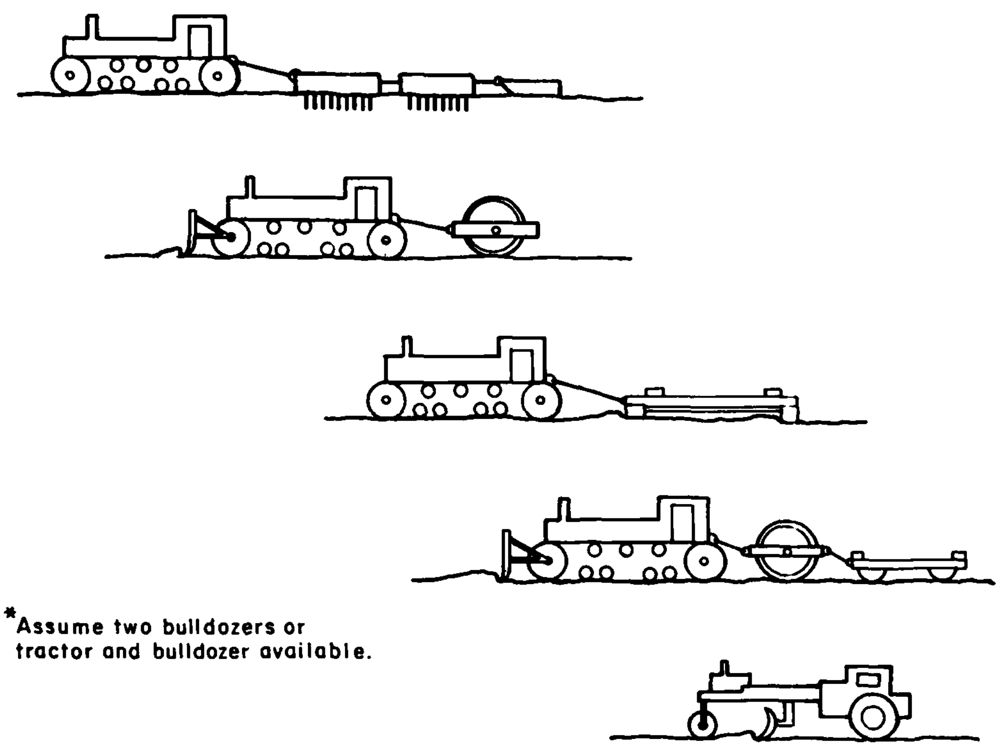
The tractor tracks ordinarily produce a more effective, although more concentrated, compaction than the roller; this should be obvious from the relative sinkage of the tracks and the roller. Therefore, it is important during the consecutive compaction passes that the tractor does not follow in the same tracks but covers the entire strip as evenly as possible. This will also result automatically in overlapping roller coverage.

As soon as the vehicle towing the roller is no longer rutting the snow surface more than 5 cm, final compaction should be accomplished by successive passes with D-7 or D-8 tractor tracks. Normally two to five passes are sufficient. Snow densities of up to 0.5 g cm^{-3} can be obtained with this method.

Final grading

On compacted snow roads, drags can be used to level the pavement surface to the desired smoothness. On snow runways, a surveyor's level may have to be used to determine if the runway surface meets the appropriate surface roughness criteria (depending on the type of aircraft). Final grading can be difficult if the compacted surface does not meet these criteria. A motorized road grader, which permits the desired accuracy control, cannot be used until the snow pavement has age-hardened sufficiently to prevent the grader wheels from

Operation	Equipment
Disaggregation	Tractor* Harrow Skid
Leveling Compaction	Bulldozer* Roller
Grading	Tractor Drag
Compaction Finishing	Bulldozer Roller Smooth Drag
Final grading	Motorized Road Grader



*Assume two bulldozers or tractor and bulldozer available.

Figure 59. Schematic of expedient snow pavement construction procedure.

rutting the surface, unless the grader is on skis and towed by a tractor. Consequently drags towed by tracked vehicles have to be used, followed by a final rolling with a corrugated or smooth roller. For a smooth surface finish, a drag of the type shown in Figure 57 can be used after the roller. Subsequent use of a wheeled, motorized road grader, which may have to be used several days after compaction, is suitable only for removing high spots; low spots filled by the grader at this stage will remain weaker than the rest of the pavement, even after compaction. Therefore, it is important that as much leveling as required be done in conjunction with the compaction process and that final grading with a road grader, some time after compaction, be limited to shaving off high spots.

Continuity of construction procedures

One of the most important considerations during the snow pavement construction process is continuity of operations, with a minimum time interval between the individual operations. This is particularly important between the disaggregation and compaction phases. The ideal procedure would be to tow a compactor immediately behind the disaggregator. However, towing a roller behind the harrow, especially if two or more harrows and a skid are used in tandem, may be neither possible nor practical. The actual procedure to be used depends on whether or not separate tractors or bulldozers are available for each of the disaggregating, compacting and grading operations. A single-tractor operation would mean completing all the processes on each individual harrow-width strip before disaggregation of the next adjacent strip could begin. The availability of two or three tractors would permit a convenient tandem-type operation with a minimal time interval (a matter of minutes) between each process.

The construction process outlined here should, under favorable temperature conditions (above –20°C), permit construction of a snow pavement capable of supporting wheel loads of heavy trucks and the Caribou class aircraft (Table 4) after 2–3 weeks of age-hardening. The integrity of the snow pavement will decrease as the temperature increases above –10°C.

Operation and maintenance

Tracked vehicles, except those with smooth rubber tracks, should be kept off the snow pavement. If this is impossible, very slow speeds should be used and sharp turns and sudden stops avoided. Particular care should be taken during warm periods. During aircraft operations, hard braking and sharp turns should also be avoided as much as possible.

Under no conditions should refueling take place on the pavement, since any fuel spilled will immediately destroy the strength of the snow pavement. Refueling should take place at designated parking areas, with the realization that these areas will be a constant source of maintenance problems.

Table 4. Fuel and water requirements for heat-processed snow pavements.

				Rate of usage		*Total required*	
Process	*Surface*	*Strips*	*Speed (km/hr)*	*Water (L/hr; gal/hr)*	*Fuel (L/hr; gal/hr)*	*Water (L; gal)*	*Fuel (L; gal)*
Steam injection	Runway (1 km × 30 m)	25 at 1.2 m wide	1	1,961; 518	144; 38	49,000; 13,000	3,600; 950
	Road (1 km × 6 m)	5	1	—	—	9,800; 2,590	720; 190
Direct heat							
T-5 snowpacker	Runway (1 km × 30 m)	15	1	—	600; 160	—	9,000; 2,400
STM-2 (USSR)	Runway (1 km × 30 m)	12	1.5	—	250; 66	—	2,000; 528
	Road (1 km × 5.5 m)	2	1.5	—	—	—	340; 90
Water application	Runway	25	1	—	—	750,000; 200,000	37,500; 10,000
	Road (1 km × 6 m)	—	1	—	—	150,000; 40,000	7,500; 2,000

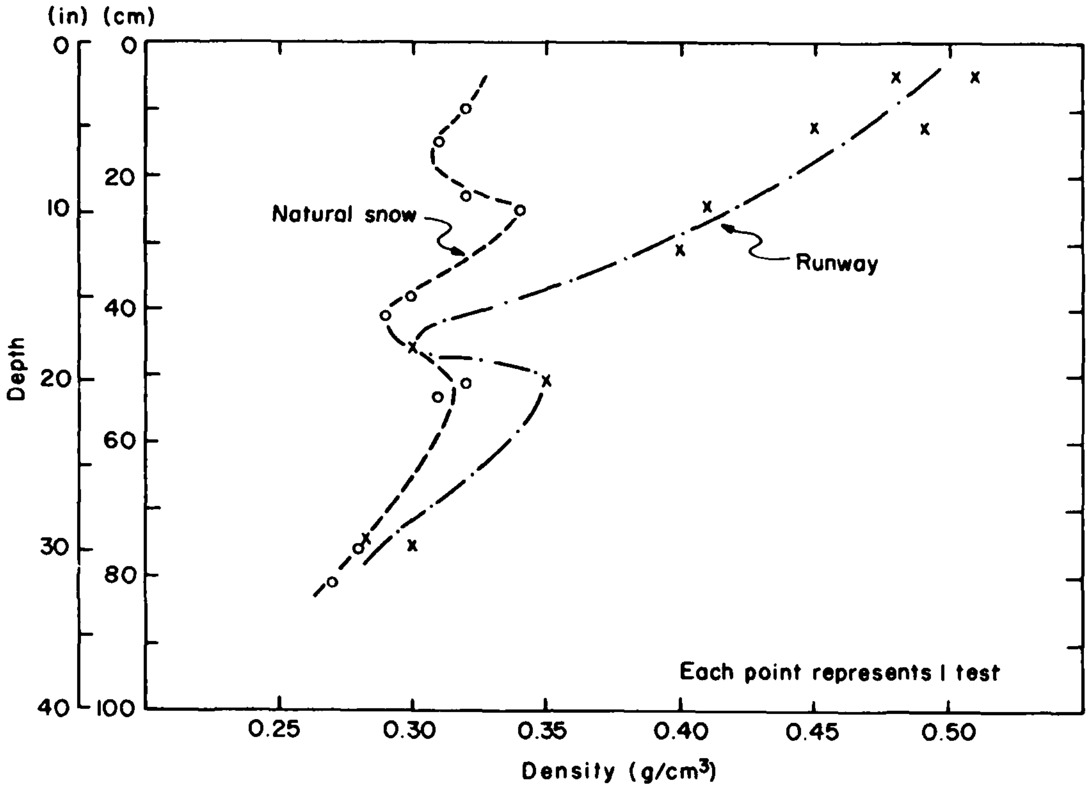


Figure 60. Density profiles of South Pole snow (Abele and Frankenstein 1967).

All debris should be kept off the pavement. Dark objects can be especially harmful by producing melt holes. Ruts and holes can be repaired by carefully filling them with fresh disaggregated snow and compacting the new snow. Some warming of the snow (without excessive melting) during placement in the ruts or holes, and while compacting, can give improved results. The repaired areas should not be disturbed until the required strength is reached through age-hardening.

Any new snowfall should be compacted as soon as possible with rollers. The thinner the snow layer to be compacted, the better the results; that is, if possible, new snow should not be allowed to accumulate to a thickness of more than a few centimeters before compaction is begun. Consequently, during heavy or prolonged snowfall, compaction may have to be done while it is snowing.

In some cases, instead of compaction, removal of any new snow may be preferable, especially if the new snow layer is several centimeters thick. For example, if the pavement has to be used shortly after a new snowfall, the compacted new snow may not have sufficient time to age-harden. Whether compaction or removal is preferable will be dictated by topography, thickness of the new snow layer, temperature, available time and equipment, etc. Ordinarily, removing new snow is more difficult than compacting it, especially on runways, because of the width of pavement. Removal also involves the danger of damaging the snow pavement below. When removing snow by plowing, care must be taken to avoid leaving snow berms at the sides of the road or runway, which may result in subsequent snow drifts on the pavement.

High-strength snow pavement construction

Processing equipment

To achieve pavement strengths required to support heavy wheel loads, such as trucks and aircraft with ground contact pressures above 5 kg cm^{-2} (70 psi), a processed and well-compacted snow layer at least 50 cm (20 in.) thick is needed. This type of depth processing requires the use of rotary snow millers (snow plows) or pulvimixers (rototillers).

The Peter snow miller (Fig. 61), equipped with backcasting chutes (Fig. 62), has been used to construct experimental snow pavements in northern Michigan, Greenland and Antarctica (Wuori 1959, 1960, 1962a, 1963a, 1963b, Abele and Frankenstein 1967, Abele 1968). The miller, originally designed for snow removal in the Swiss Alps, has a horizontally mounted, closed drum with spiral blades. The 1.2-m-diameter, 2.7-m-long drum rotates at 225–305 rpm and directs the snow into the specially

Figure 61. Peter snow miller.

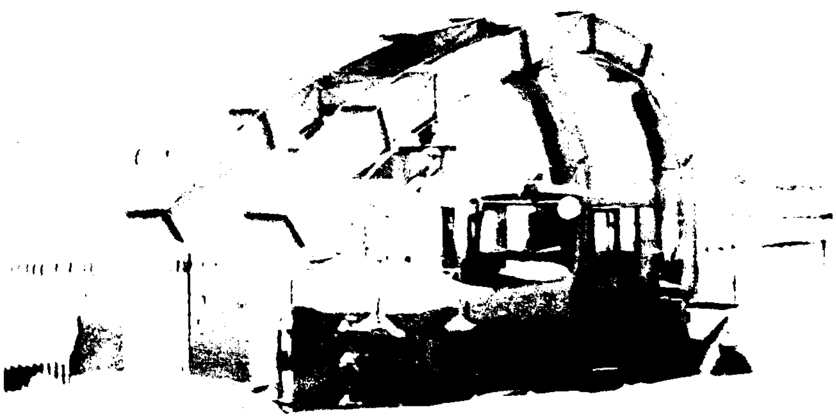


Figure 62. Peter snow miller with back-casting chutes.

fabricated ejection chutes, which guide the snow over the miller. During operation, the chutes oscillate laterally, so that the snow is deposited behind the miller in a reasonably even thickness. Figure 92 shows the miller in operation, towing a vibratory compactor.

The Peter miller is capable of processing undisturbed snow up to 1.2 m deep. The density of the processed snow is approximately 0.5 g cm^{-3}, so if the mean density of the undisturbed snow is 0.25 g cm^{-3}, the resulting processed snow layer is 0.6 m thick. If the initial mean density of the snow is increased to 0.3 g cm^{-3} by precompaction, the resulting processed snow layer would be approximately 0.7 m thick. (During field tests it was found that the Peter miller can actually cut to 1.5 m deep by undercutting, i.e. by keeping the top of the cutting blades as much as 30 cm below the snow surface and

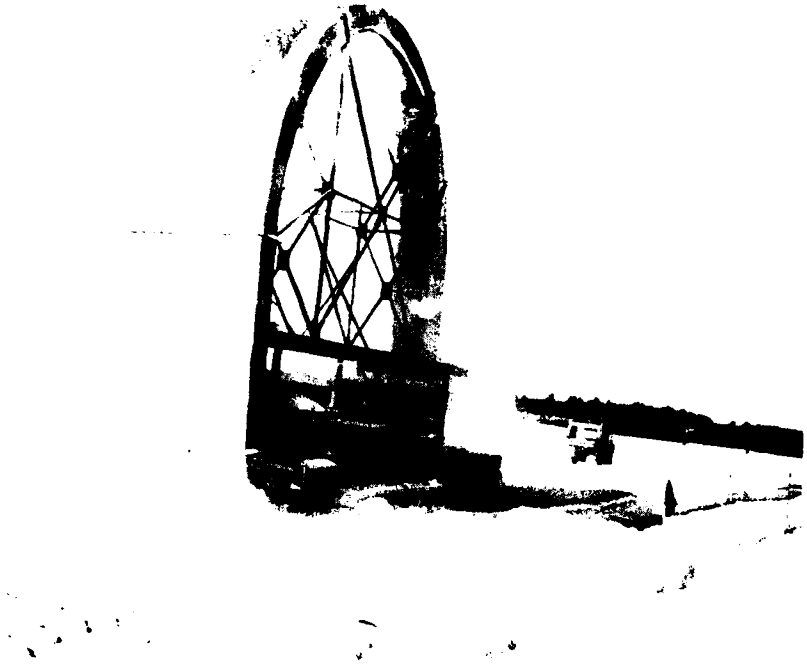


Figure 63. Snowblast miller with back-casting chutes.

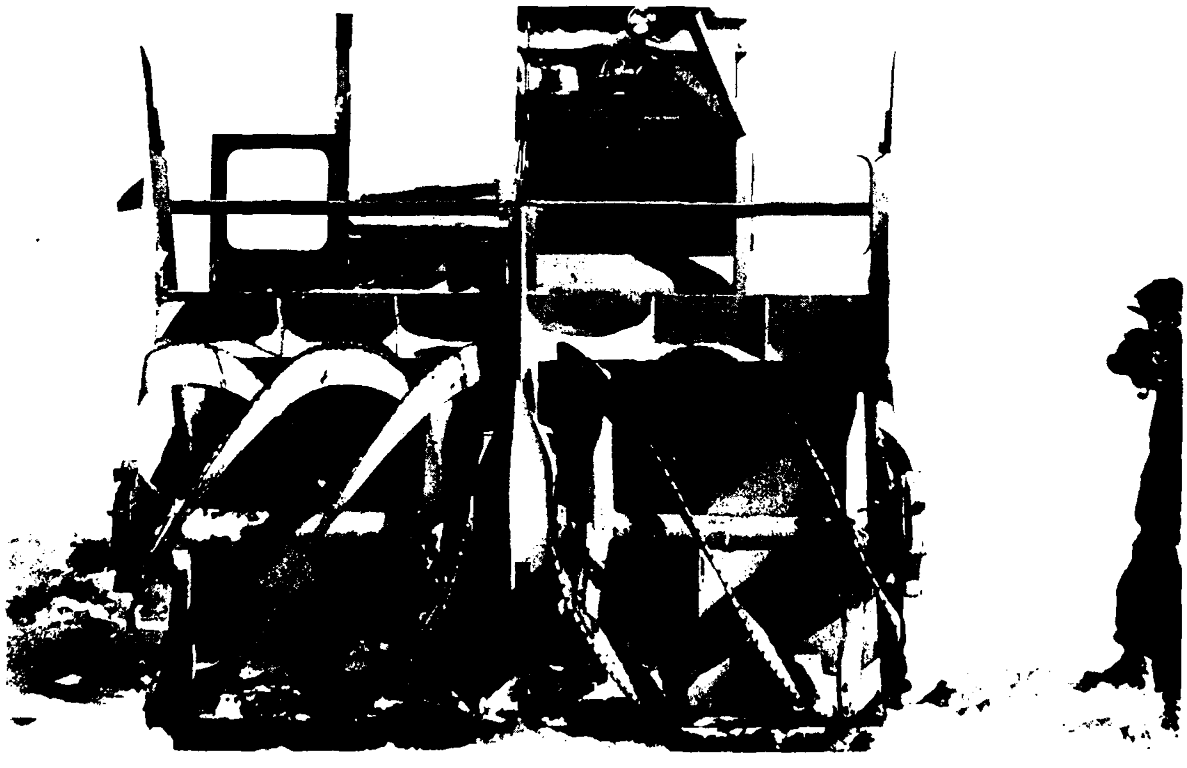


Figure 64. Snowblast milling blade arrangement.

forcing the snow above the undercut to fall into the milling drum with the hinged guard plates located above the drum; refer to Fig. 61.)

The Rolba Snowblast miller, which in a wheeled version is also used primarily for snow removal in the Swiss Alps, as well as in the U.S., has been used as a snow processor for experimental snow pavement construction in northern Michigan and Greenland (Jackovich and Wuori 1963, Wuori 1963a, 1963b). The standard rotary snow plow was mated with a D-6 Caterpillar tractor and equipped with a special back-casting chute (Fig. 63). The miller is equipped with helical cutter blades (1.3-m diameter, 2.6 m cutting width, 260 maximum rpm) and an impeller (1.3-m diameter, 320 maximum rpm), which transfers the snow from the cutter into the chute (Fig. 64). The chute contains baffles for distributing the snow evenly behind the miller.

The density of the snow processed with the Snowblast was the same as that processed with the Peter miller. The Snowblast snow had a slightly better grain size distribution than the Peter snow (Wuori 1963a). Tests with other types of rotary snow millers produced results that, in terms of snow properties, were similar to those of the Peter and the Snowblast (Wuori 1959).

The pulvimixer, developed by the Naval Civil Engineering Laboratory (Coffin and Moser 1961), has been used extensively for road and runway construction in Antarctica (Moser 1963, 1964, Moser and Sherwood 1966, Barthelemy 1975b). It had also been used for constructing a compacted snow parking lot for the 1960 Winter Olympic Games at Squaw Valley, California (Coffin 1959, Moser 1962). The schematic of the pulvimixer is shown in Figure 65 and the rotor blade arrangement in Figure 66. The rotor on the early model (Model 24) was 2.4 m long and had a diameter of 0.61 m. The rotor diameter in the later model (Model 42) was increased to 1.07 m, permitting a cutting depth of up to 0.8 m.

Unlike the Peter miller and the Snowblast, which are self-propelled, the pulvimixer is towed by a tractor (Fig. 67). One of the operational problems of the Peter miller and the Snowblast was the difficulty in steering while in a full cut. The towed pulvimixer is much easier to control, and forward speeds of up to 2.75 km hr^{-1} can be maintained. The rear ski of the pulvimixer is the same width as the rotor and acts as a leveler (Fig. 68). In a full cut (1.2–1.5 m), the forward speed of the Peter miller and the Snowblast is limited to slightly more than 0.5 km hr^{-1}.

Because of the helical blade arrangement on both the Peter and the Snowblast, the snow is disaggregated by continuous shaving of the snow face. The pulvimixer blades (L-shaped tines) chip at the snow face, resulting in disaggregated snow that is coarser than that produced

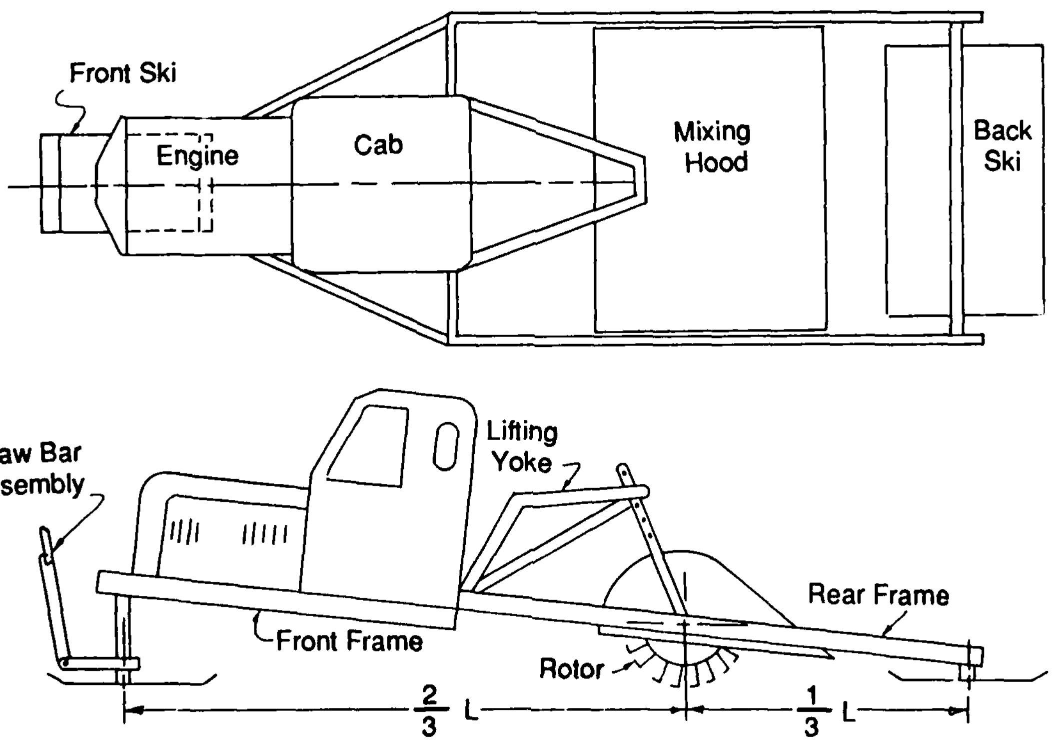


Figure 65. Schematic of NCEL snow pulvimixer.

Figure 66. Pulvimixer rotor blade arrangement. (Official photograph, U.S. Navy.)

Figure 67. Tractor-drawn pulvimixer. (Official photograph, U.S. Navy.)

Figure 68. Pulvimixer with rear skid. (Official photograph, U.S. Navy.)

by the Peter or the Snowblast. The geometric mean diameter of the pulvimixer snow grains is approximately 0.9 mm, compared with approximately 0.6 mm for the Peter and Snowblast snow grains (Fig. 17). A higher percentage of fines in processed snow is beneficial for increasing both the rate of age-hardening and the ultimate strength. Therefore, helical blades that produce a shaving action are preferable to blades or tines that disaggregate snow by chipping.

The principal advantages of the Peter miller, the Snowblast or similar rotary snowplows are the better disaggregation of the snow and a thicker snow pavement (50% thicker than that made with the pulvimixer). A tractor-drawn pulvimixer, however, is much easier to operate and control and can be used at a forward speed five times that of a tracked rotary snow miller.

Other types of mixers, tillers or disaggregators, usually modified soil mixers, are not well suited for high-strength snow pavement construction because of their limited cutting depth (usually less than 0.5 m).

Application of heat

The snow pavement surface strength can be increased by introducing free moisture into the snow, which results in an increase not only in density but also in bonding, since the moisture acts as a rapid bonding agent. The moisture can be introduced in two ways: by applying heat during processing and thus melting some of the snow, or by adding water during or after processing. To gain the most benefit, compaction has to be done immediately after the addition of heat or water.

The application of heat or addition of water requires a considerable amount of energy and therefore should be considered for only a relatively thin surface layer of the snow pavement. Since the required strength in a snow pavement decreases rapidly with depth (Fig. 45), the high-strength surface layer does not have to be very thick (<30 cm) if it rests on a processed snow base. For example, at a depth equal to the radius of the load contact area, the required pavement strength is only between 50 and 60% of the required surface strength (Fig. 45).

A reasonably uniform distribution of free moisture in processed snow can be obtained by applying steam during disaggregation with a rotary tiller. During processing of snow having an initial density of 0.3 g cm^{-3} at a temperature of –23°C, 1 cm^3 of condensate in steam applied at a pressure of 7 kg cm^{-2} creates 8 cm^3 of water. At a forward speed of 1 km hr^{-1} and a cutting depth of 30 cm, the moisture content in the processed snow would be 15% or less, depending on the efficiency of injecting

Figure 69. ERDL heat-equipped T-5 Snowpacker.

Figure 70. Water penetration from heat-processed snow layer into base layer.

steam into the snow. For a 1.2-m-wide cut, the required amount of water would be approximately 2000 L hr^{-1}, which would need almost 150 L hr^{-1} of fuel to produce the necessary energy rate of almost 1.5×10^6 kcal hr^{-1}.

Increasing the surface strength characteristics of a processed snow runway 1 km long and 30 m wide by applying steam as discussed above would require 3,600 L of fuel to produce 49,000 L of water required for the steam. The fuel requirements for a 6-m-wide road would be 720 L km^{-1} to produce the required 9,800 L of water per kilometer of road (Table 4).

The application of hot air from open-flame burners during snow processing has been tested with a variety of models developed by the U.S. Army Engineer Research and Development Laboratories (Beigbeder 1951, 1952, 1958). This method of heat processing (a row of burners mated with a pulvimixer) was used to reinforce the surface of pulvimixer-dry-processed snow runway pavements in Greenland during the 1950s, and a more advanced model (Snowpacker T-5) was tested on top of a Peter-miller-processed snow base (Wuori 1963a, 1963b).

A variety of mechanical and operational problems hampered the performance of all of the heat-equipped pulvimixers (models T-1 through T-5). The fuel consumption was extremely high. For the construction of a 60-m-wide, 3000-m-long snow runway in Greenland, approximately 75,000 L of fuel was used by the engines and burners of the heat-equipped pulvimixers, plus 26,500 L of fuel used by the towing tractors. Some areas received two passes of heat processing, which may explain the 12,500 L per 30,000 m^2 fuel consumption rate (refer to the 1-km × 30-m runway area used for comparison purposes in Table 4).

The T-5 snowpacker (Fig. 69) used 600 L of fuel per hr. At a forward speed of 1 km hr^{-1} and a 2-m-wide cut, the T-5 would require 9000 L of fuel to heat-process a 1-km × 30-m runway area (Table 4). The rate of energy output is approximately 5×10 kcal hr^{-5}, which is more than three times higher than that for the steam application method.

Inspection of the profile of a 1-m-thick snow pavement, which had been constructed by dry-processing with a Peter miller and 4 days later heat-processing with the T-5 snowpacker to a depth of 12 cm, revealed that the heat applied had produced an unnecessarily high amount of free water (Wuori 1963a). Most of the water had drained out of the heat-processed layer; some of the water had accumulated on top of the hardened dry-processed snow, and some had percolated into it, forming ice roots (Fig. 70). Obviously a considerable amount of heat had been wasted.

The 12-cm-thick heat-processed surface layer on top of a dry-processed base and compacted with a pneumatic-tire roller resulted in a snow pavement capable of supporting heavy aircraft wheel loads. One week after construction, the unconfined compressive strength of the surface layer was approximately 15.5 kg cm^{-2} (220 lb in^{-2}). This type of pavement would be capable of supporting a KC-135 (or Boeing 707) aircraft.

The USSR has developed a thermo-vibrating snow compactor (STM-2), which is a tractor-drawn pulvimixer equipped with a hot air fan and a vibratory compactor (Fig. 71) (Volkova 1979). The unit uses 250 L of fuel per hour, the forward speed is 1.5 km hr^{-1}, and the width of cut is 2.8 m. A 1-km × 30-m runway strip would therefore require approximately *2000 L* of fuel (Table 4). A 5.5-m-wide road would require approximately 340 L of fuel per kilometer.

Water is ordinarily applied after the snow pavement has been compacted and leveled. The water usually penetrates only 10–20 cm, resulting in an ice–snow pavement surface. This procedure for increasing the

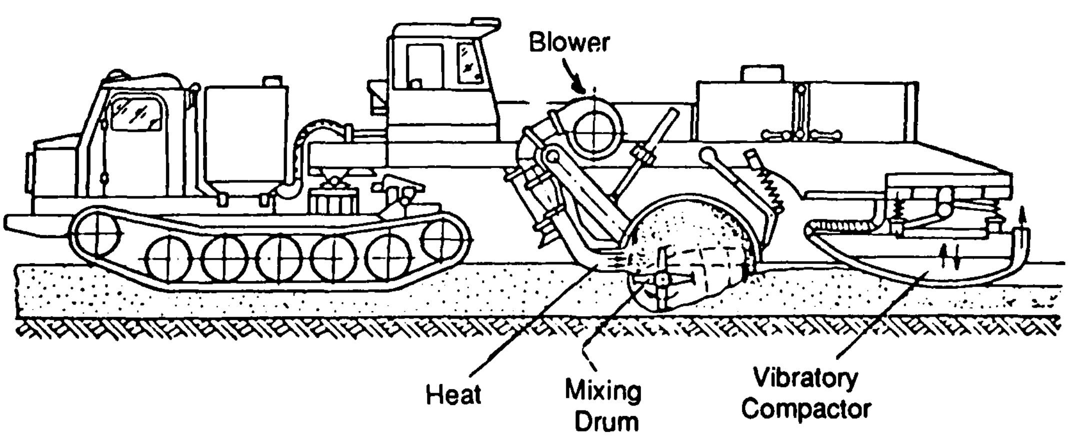


Figure 71. Soviet thermo-vibrating snow compactor (Volkova 1979).

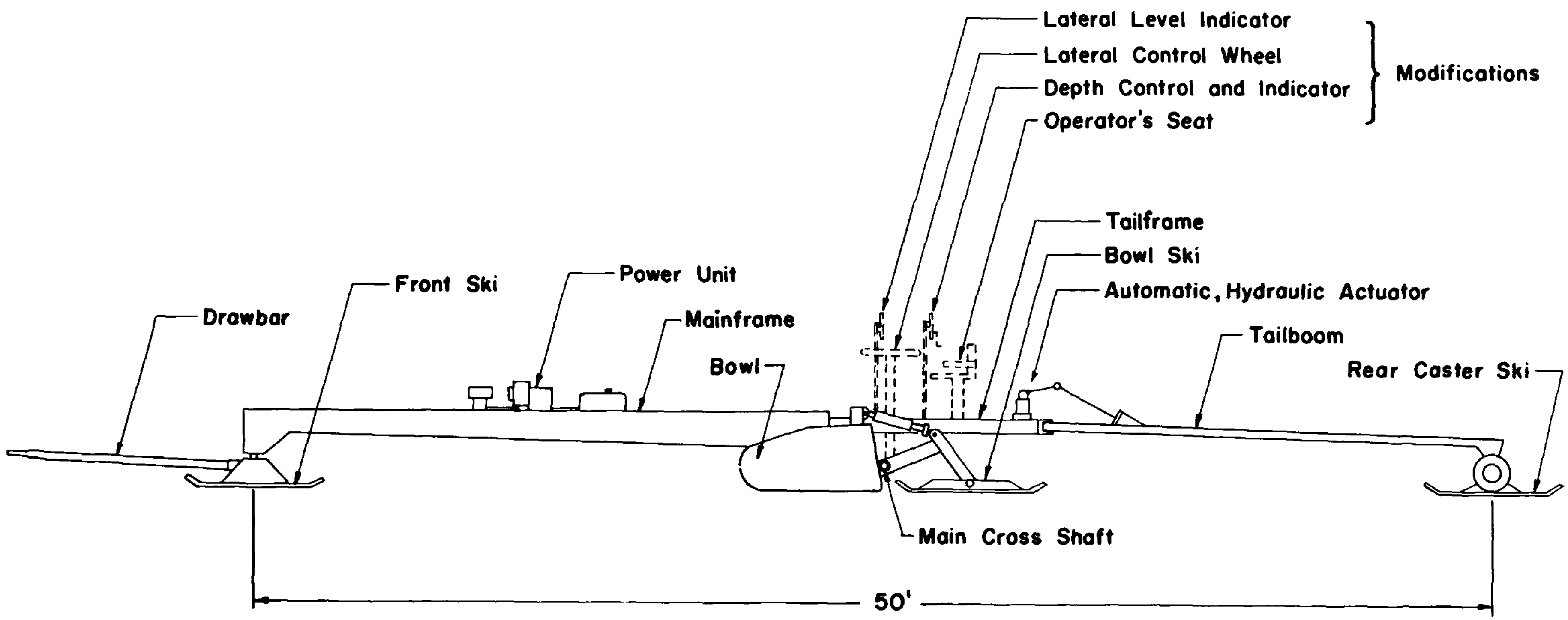


Figure 72. Gurries snow planer, GP-50.

strength of a snow pavement requires large quantities of water. For satisfactory results, 2.5 cm of water is required (Adam 1978b, Wuori 1963b). Therefore, for a 1-km × 30-m runway strip, 750,000 L of water would be required. To estimate the corresponding fuel requirements, it can be assumed that 1 L of fuel is needed to produce 20 L of water by melting snow (Rand 1982). Unless a source of water, such as a lake or river, is available nearby, the fuel requirement for the runway strip would be 37,500 L (Table 4). For a 2.5-cm water application, a 6-m-wide road would require 150,000 L of water and 7,500 L of fuel per kilometer.

The logistics requirements for water application are significantly higher than those for other types of heat application methods. The procedure is also complicated by the difficulty of keeping the water supply pipes and nozzles on the spraying equipment from freezing, with the degree of difficulty increasing with decreasing temperature. While this procedure may frequently be suitable for reinforcing snow pavements in Alaska or Canada, where temperatures are less extreme and sources of water often available, it may not be practical at the South Pole, for example.

Leveling equipment

Since a snow pavement surface should be leveled immediately after processing while the snow is still relatively cohesionless and the compaction should be done as soon as possible after leveling, it is important that the leveling operation not be unduly time consuming. To complete the leveling as efficiently as possible and to obtain a surface suitable for aircraft operations, long-base leveling equipment is required for snow runway construction and is very desirable for snow road leveling as well.

A modified field planer (Gurries, model GP-50), originally designed for leveling the base course surfaces of roads and airfields to a high degree of accuracy, has been used with very good results on experimental snow pavements (Wuori 1963c). The ski-equipped planer (Fig. 72) has an effective planing length of 15 m. The cutting depth of the 3.6-m-wide, 3-m^3-capacity bowl is

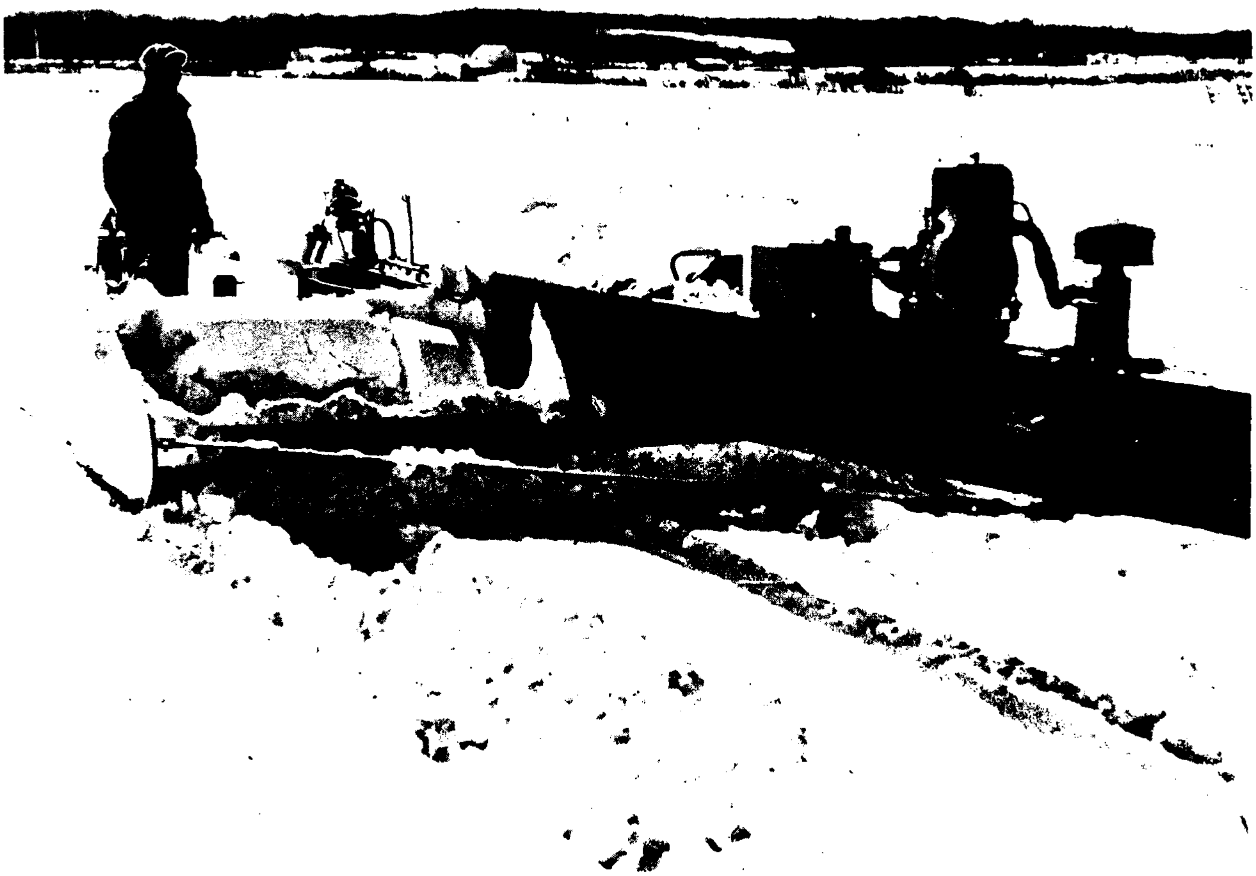


Figure 73. Snow planer in action.

automatically controlled by the rear ski through a hydraulic actuator valve, which, in turn, controls the hydraulic cylinders attached to the bowl skis. The actuator valve can be adjusted manually to set the depth of cut relative to the bottom of the rear ski. Since the planing action is automatic, no operator is required, except for resetting of the actuator valve if there is a need to change the cutting depth. The operator can also manually adjust the cross slope of the blade.

The planer can be towed by the processing unit (a rotary plow); however, during tests the leveling was usually more successful if the planer was towed by a bulldozer, with the rough leveling being done by the bulldozer blade. The planer (before the modifications shown in Figure 72) is shown in action in Figures 73 and 74.

Two major modifications to the planer would be required to further improve the leveling operation: a larger

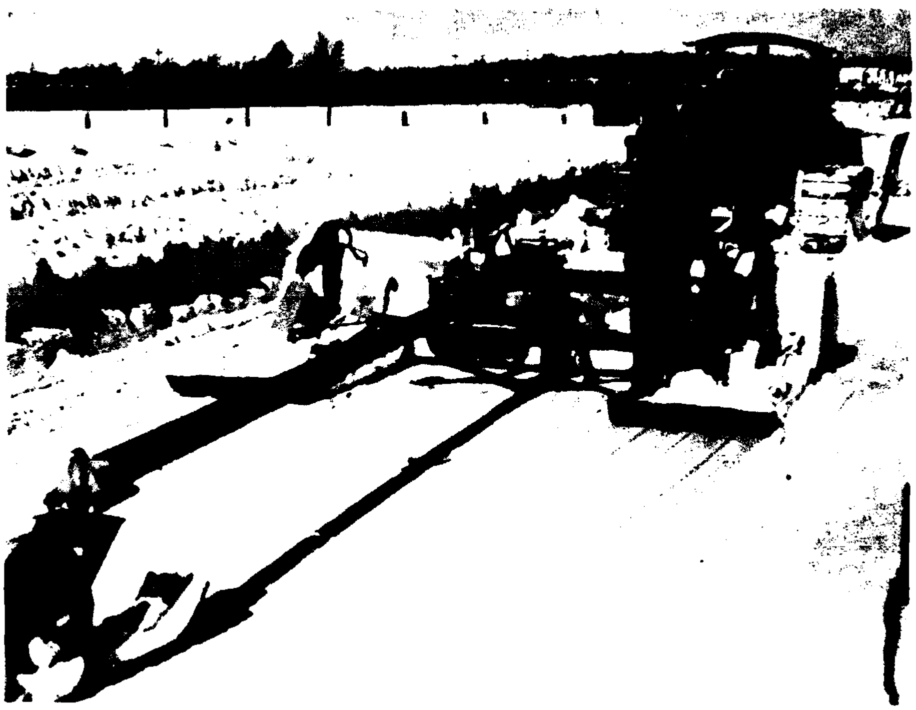


Figure 74. Snow planer, rear view.

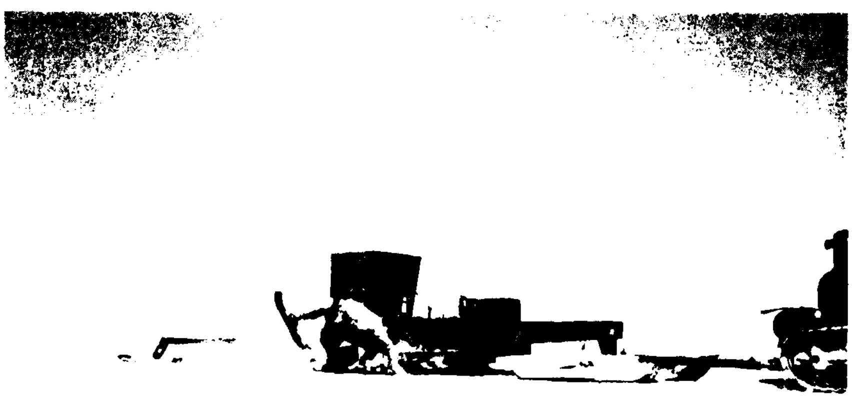


Figure 75. Gurries automatic snow planer (GARB-44).

bowl capacity and a reversible screw-type distributor in the bowl to keep the snow more evenly spread in the bowl.

A more advanced version of this type of planer, the Gurries Automatic Road Builder (model GARB-44) modified for operation on snow (Fig. 75), has been tested in Michigan and used for runway construction in Greenland and Antarctica (Abele 1968).

The GARB operates on the same principle as the planer (GP-50), but it has the following additional features:

- A larger bowl (7.6 m^3);
- A reversible conveyor screw in the bowl;
- The ability to control the depth of cut using either the rear ski (Fig. 76) or the left or right tracer ski (Fig. 77), so that the cut can be referenced from the adjacent, previously leveled area; this feature is especially convenient for runway leveling;
- The ability to set and maintain the cross slope of the cut automatically;

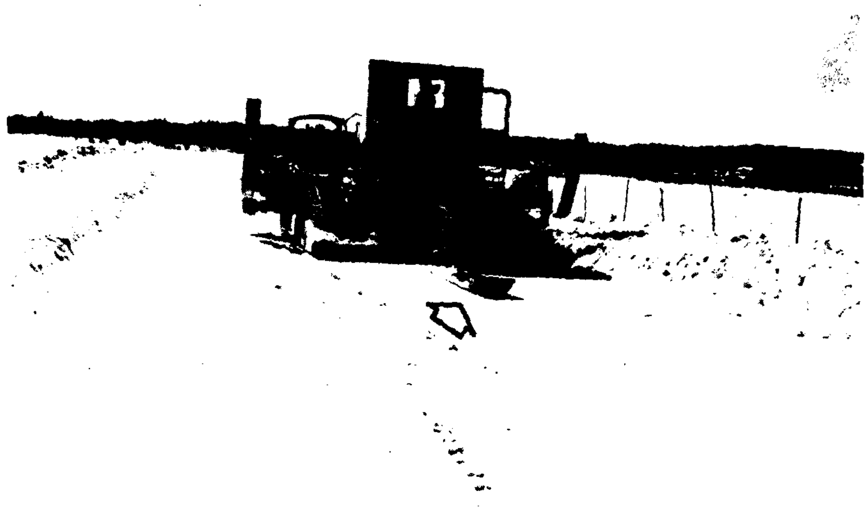


Figure 76. Long-wheelbase leveling method (GARB-44).

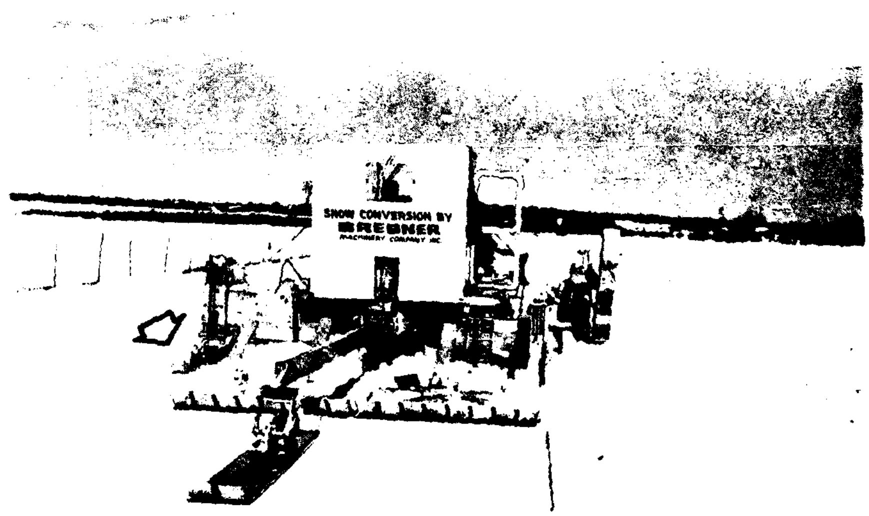


Figure 77. Side-tracer-ski leveling method (GARB-44).

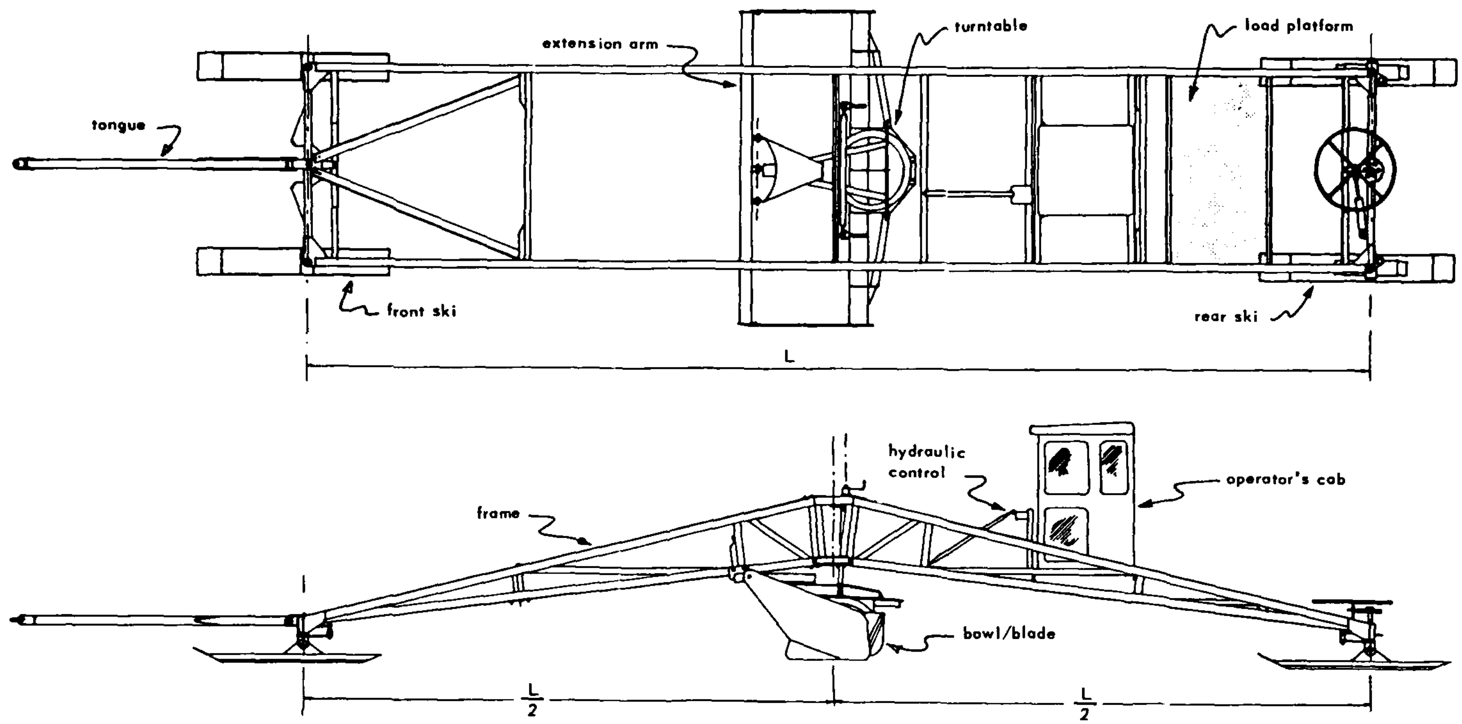


Figure 78. Schematic of NCEL 40-ft snow plane.

- A cab for the operator; and
- Wide skis, which cover the entire leveling width.

This leveler is well suited for the final grading of large areas, such as runways, where the pavement must be leveled accurately. In the tests the leveler was towed with a tractor, usually at a speed of 3–4 km hr^{-1}.

The major problem experienced in Antarctica was the sensitivity of the hydraulic system to temperature changes and to the type of hydraulic fluid used, which at times reduced the performance and therefore the quality of the leveled surface. (The finished surface had low-frequency undulations because the hydraulic system controlling the cutting depth produced slow, delayed overreactions to minute imperfections sensed by the tracer ski.) This problem was not experienced during the previous tests in Michigan and Greenland, when the proper hydraulic fluid was available.

The use of the GARB can be justified only where very great accuracy of the surface is required and when the shipment of this type of equipment (with a gross weight of almost 20 metric tons) does not place an undue burden on the overall logistics capabilities. Ordinarily a sufficiently smooth snow pavement surface can be produced with less costly equipment.

NCEL has developed long-base, hydraulically operated, manually controlled snow planes; the first model was 12 m long, and a later model was 24 m long (Fig. 78 and 79) (Moser 1961, NCEL 1974a). The 24-m model was designed specifically for fine leveling of runways in Antarctica. Although it performed satisfactorily as a finishing planer, it could not be used for rough grading because it was structurally inadequate to withstand stresses imposed by the 5-m-long blade with a full load. Both snow planes were towed by D-4 tractors.

A towed, leaning-wheel, hand-operated road grader (Fig. 80) was used in Greenland on compacted snow runways (Moser 1961, Wuori 1959). This type of grader could produce a more level surface than a bulldozer, but the results were not nearly as satisfactory as those of the NCEL snow planes or the Gurries planers. It was not suitable for rough leveling because of the low-volume-capacity blade and the difficulty of controlling the blade with manual controls (Wuori 1960).

Leveling of winter snow roads is usually accomplished with bulldozers and drags; occasionally road graders are used (Adam 1978b). For permanent snow road construction and maintenance in Antarctica, the NCEL 12-m or 24-m snow planes were used (Barthelemy 1975a, NCEL 1972a).

Compaction rollers

Corrugated and smooth steel rollers are most commonly used for snow pavement compaction. A 1.2-m-diameter corrugated roller (Wuori 1959, 1962a), used on a snow runway in Greenland, is shown in Figure 81. A 2.4-m-diameter smooth roller, used for most of the snow road and runway construction projects in Antarctica (Camm 1961), is shown in Figure 82. Occasionally, heavy 3-m-diameter rollers have been used (Freberg 1952). Figure 83 shows a 10-ton, 3-m-diameter, segmented U.S. Navy roller, consisting of four 61-cm-wide, individually suspended units (Gerdel and Diamond 1954).

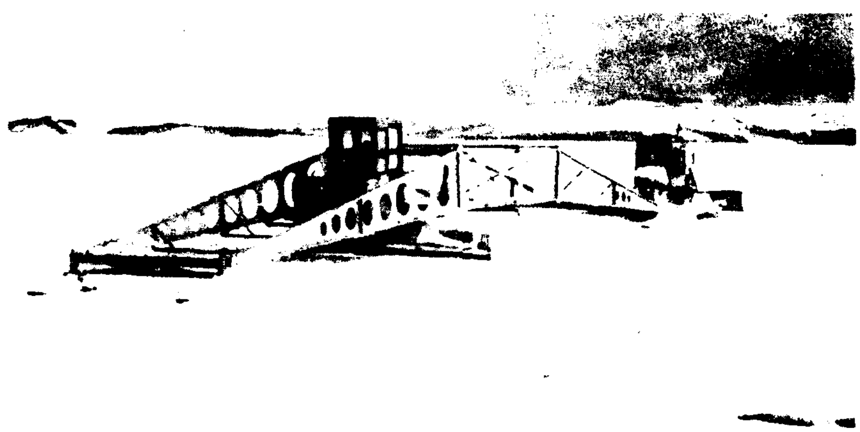


Figure 79. NCEL 80-ft snow plane. (Official photograph, U.S. Navy.)

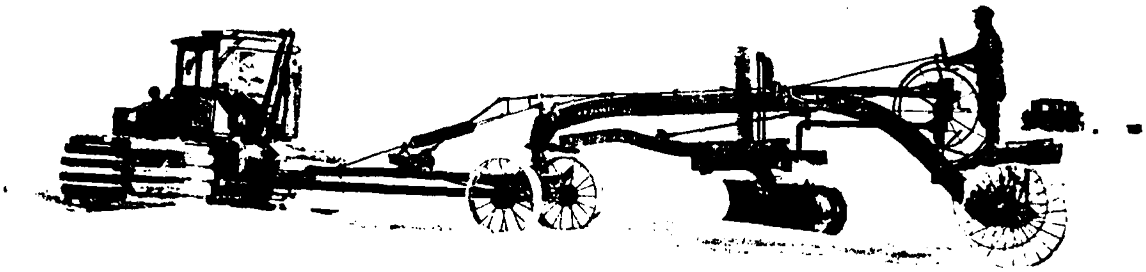


Figure 80. Leaning-wheel grader.

Figure 81. D-8 LGP tractor with corrugated roller.

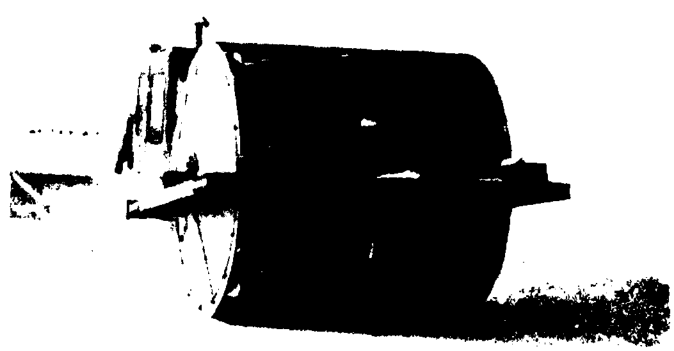


Figure 82. NCEL 8-ft-diameter smooth roller. (Official photograph, U.S. Navy.)

Figure 83. U.S. Navy 10-ft-diameter segmented roller.

Figure 84. Sheepsfoot roller.

The standard sheepsfoot roller (Fig. 84) produces a waffle-type snow surface (Fig. 85) and is not as suitable for snow compaction as other types of rollers (Wuori 1959, 1960, 1963b). A 13-wheel pneumatic-tired roller (Fig. 86) is very effective for surface hardening after compaction with steel rollers (Camm 1961). The carriage platform can be loaded to produce tire contact pressures of 3 kg cm^{-2} and more (Barthelemy 1975a, NCEL 1972a). However, this type of high-pressure roller should be used only after the snow pavement surface has been previously compacted and sufficiently hardened to prevent the tires from sinking more than 1 or 2 cm. The towing equipment should be a low-ground-pressure wheeled vehicle.

The effectiveness of compaction is increased with multiple passes of a roller. With each successive pass, the sinkage of the roller decreases, thus decreasing its ground

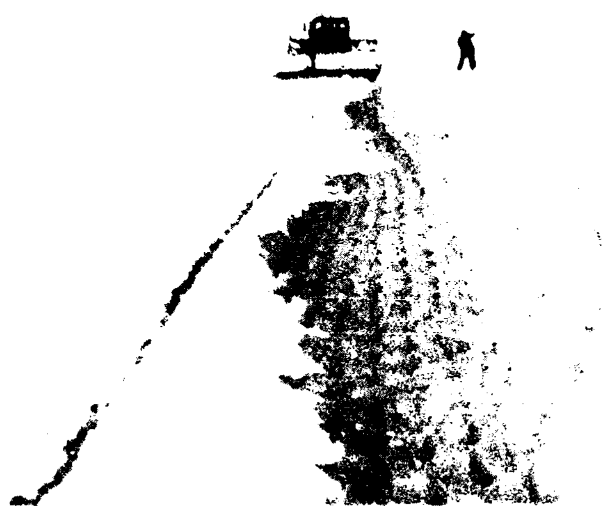


Figure 85. Snow surface after sheepsfoot roller compaction.

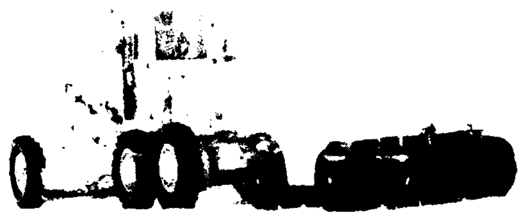


Figure 86. NCEL 13-wheel roller. (Official photograph, U.S. Navy.)

contact area and therefore increasing its contact pressure. That is, the pressure produced on the snow surface by the roller is automatically increased with each pass. The pressure can be increased further by adding weight to the roller.

For example, Figure 87 shows the pressure-vs-sinkage relationship for a 2.4-m-diameter, 2.4-m-long, 4650-kg roller. For small sinkages (relative to roller diameter), the pressure p varies as the reciprocal of the square root of sinkage z:

$$p = az - 0.5 \qquad (12)$$

where the constant a is a function of the roller weight and size (assuming a constant pressure over the roller–snow contact area).

During tests of this particular roller (Fig. 82), snow density and rammsonde hardness data were obtained and compared with the roller sinkage data (Camm 1961). The sinkage vs density and ram hardness relationships are shown in Figures 88 and 89, respectively. Both illustrate the extent of the roller sinkage in snow for particular density and hardness characteristics.

It is important that the multiple passes with a roller be done as quickly as possible (within a few hours after processing) to achieve the maximum benefit before the sintering process has progressed too far.

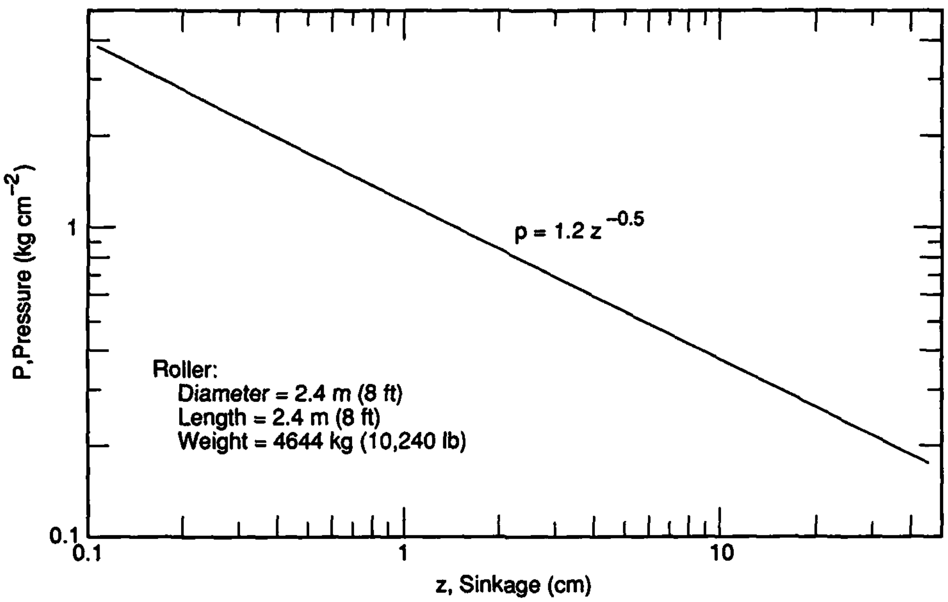
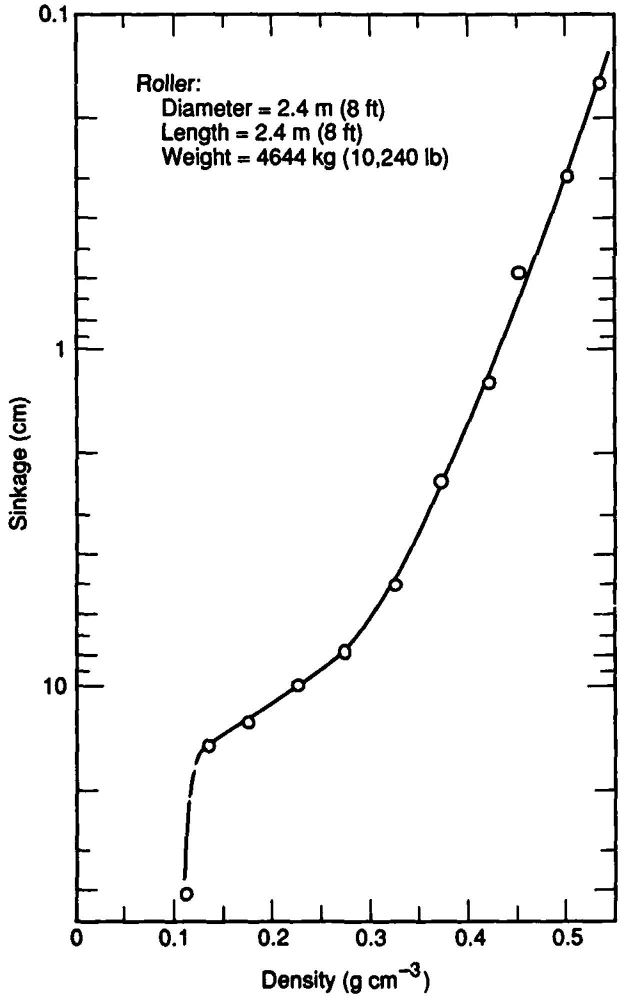


Figure 87. Pressure vs sinkage of an 8-ft-diameter, 5-ton roller. (Data from Camm 1961.)



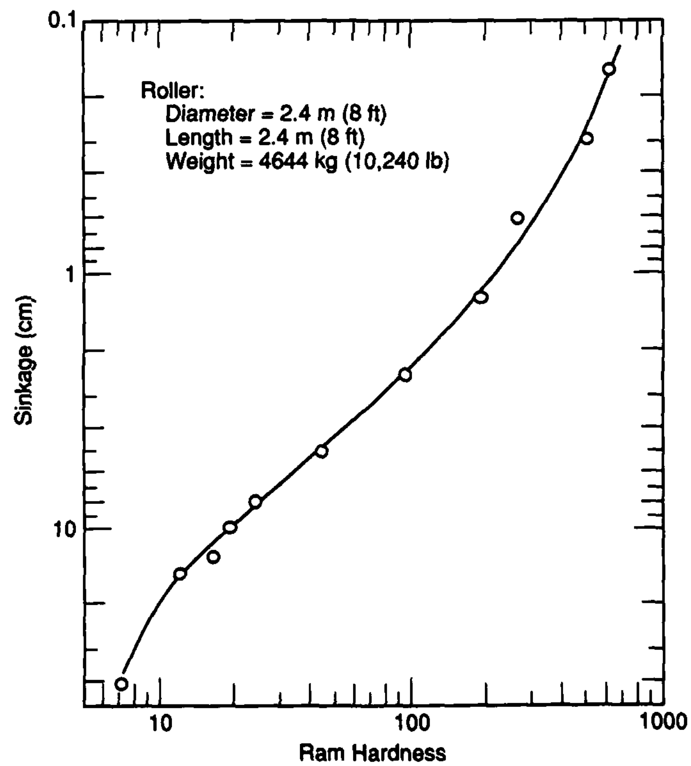


Figure 88. Sinkage of roller as a function of snow density. (Data from Camm 1961.)

Figure 89. Sinkage of roller as a function of ram hardness. (Data from Camm 1961.)

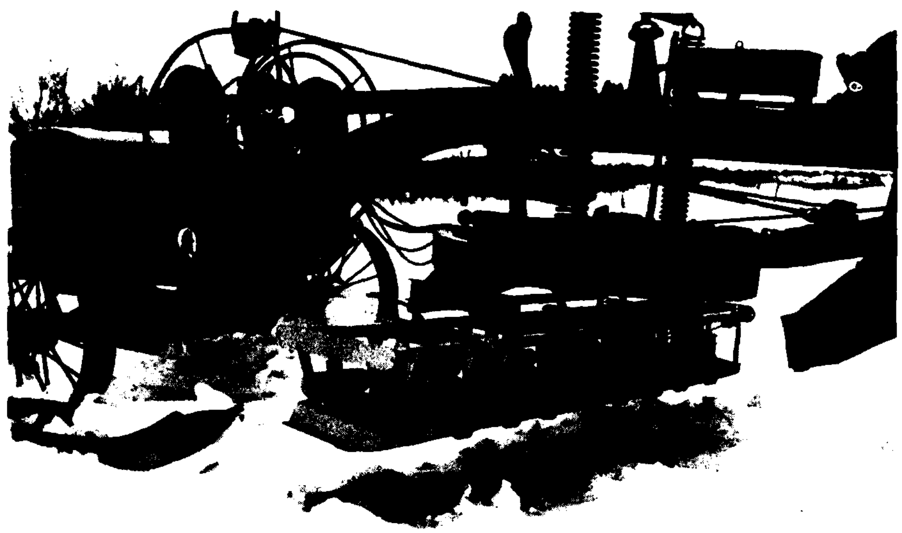


Figure 90. Vibratory compactors on a grader chassis.

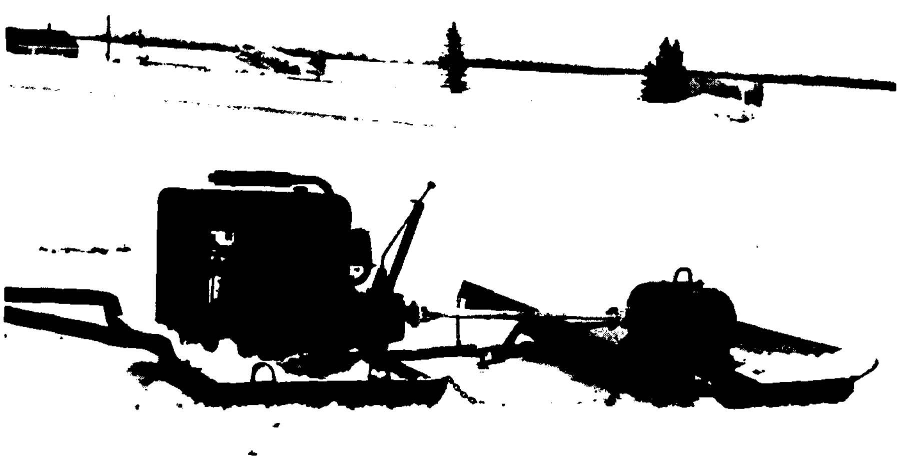


Figure 91. Small vibratory compactor.

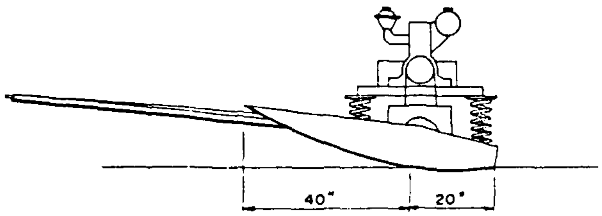
Vibratory compactors

Plate-type compactors are effective for increasing the density of newly processed snow. Figure 90 shows a row of five small, electrically operated Jackson vibratory compactors, with a frequency range of 2000–4000 cpm, installed on a ski-equipped road grader.

During tests it was observed that if the processed snow (density = 0.50 g cm^{-3}, T = 7°C) was compacted immediately, the mean snow density in the top 30 cm was increased to 0.57 g cm^{-3}. Compaction one hour after processing increased the mean density to 0.53 g cm^{-3}. Vibratory compaction 24 hours after processing had no beneficial effect, except at the very surface (Wuori 1959). Two passes with the compactor, within a few hours after processing, produced slightly better results than one pass, but three passes resulted in only negligible further densification. Changes in the vibration frequency between 2000 and 4000 cpm did not appreciably influence the resulting density, the 4000-cpm frequency being slightly less effective than either the 2000- or 3000-cpm frequencies (Wuori 1960).

A similar light, towed vibratory compactor is shown in Figure 91. Because of its low contact pressure (approximately 0.03 kg cm^{-2}), the compaction was limited to the surface 20–30 cm.

Figure 92 shows a larger, 1500-kg vibratory compac-



Weight	3300 lb
Length (tot.)	110 in.
Width	78 in.
Engine	14 hp "Wisconsin"
Frequency	2000 vpm
Amplitude	0.075 in.
Contact pressure	≈ 2 psi

Figure 92. Vibratory compactor towed by Peter miller.

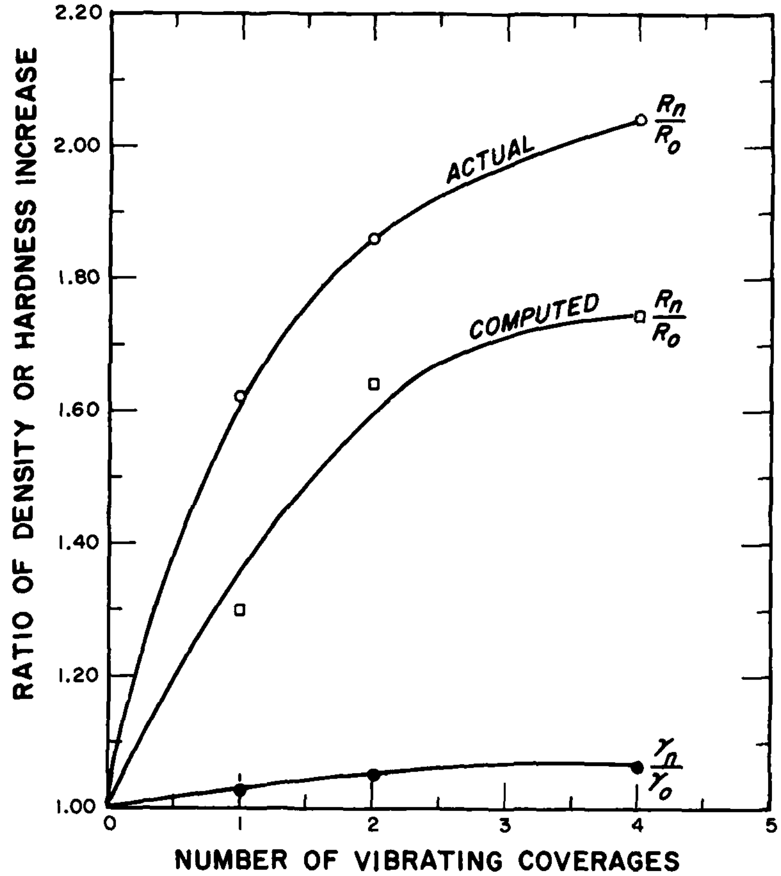


Figure 93. Effect of vibration on snow density or hardness (Wuori 1965).

tor, Vibro-Plus CS-40, with a frequency of 2000 cpm and a contact pressure of 0.14 kg cm^{-2}, being towed by the Peter miller. When used in this manner, the compactor was effective for increasing the snow density from 0.5 g cm^{-3} to almost 0.6 g cm^{-3} in the top 10 cm and to 0.56 g cm^{-3} at the 50-cm depth (Wuori 1965). The forward speed of the Peter miller was approximately 10 m min^{-1}. The effectiveness of compaction did not vary significantly when towed by a tractor at speeds of 9–40 m min^{-1}.

During tests with the CS-40 model vibratory compactor, it was observed that the increase in the mean density of processed snow for the 0- to 70-cm depth was not very significant after more than one pass (Wuori 1965). The mean density of 0.557 g cm^{-3} after one pass was increased to 0.587 g cm^{-3} after four passes. However, when rammsonde hardness measurements were made after 11 days, the increase in hardness with increasing number of compaction passes (up to four passes) was much more significant than that implied by the density data. Figure 93 illustrates the results when the density and hardness data are plotted as a ratio of

$$\frac{\text{snow property after } n \text{ compaction passes}}{\text{snow property before compaction}} = \frac{\gamma_n}{\gamma_o} \text{ or } \frac{R_n}{R_o} \qquad (13)$$

vs the number of vibratory compaction passes. It is possible that the vibratory action causes some favorable rearranging of the snow grains and better grain-to-grain contact, thus producing a snow grain matrix that is more conducive to the age-hardening process not fully represented by the density of the snow mass. The effectiveness of vibratory compaction of processed snow is illustrated in Figure 94.

Although densification was achieved to a greater depth when the snow was compacted immediately after processing, the compaction of the top 10–20 cm was more effective when done four hours after processing (Fig. 95). Consequently the results are best if vibratory compaction is done immediately after processing and again a few hours later. Vibratory compaction a day later

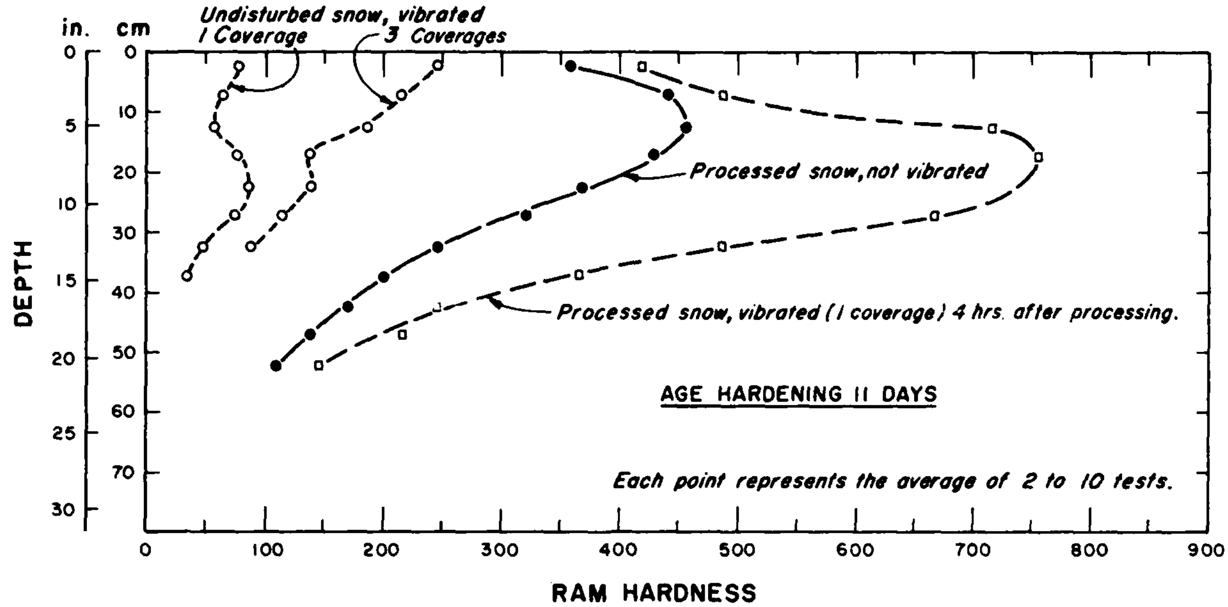


Figure 94. Effect of vibratory compaction of snow (Wuori 1965).

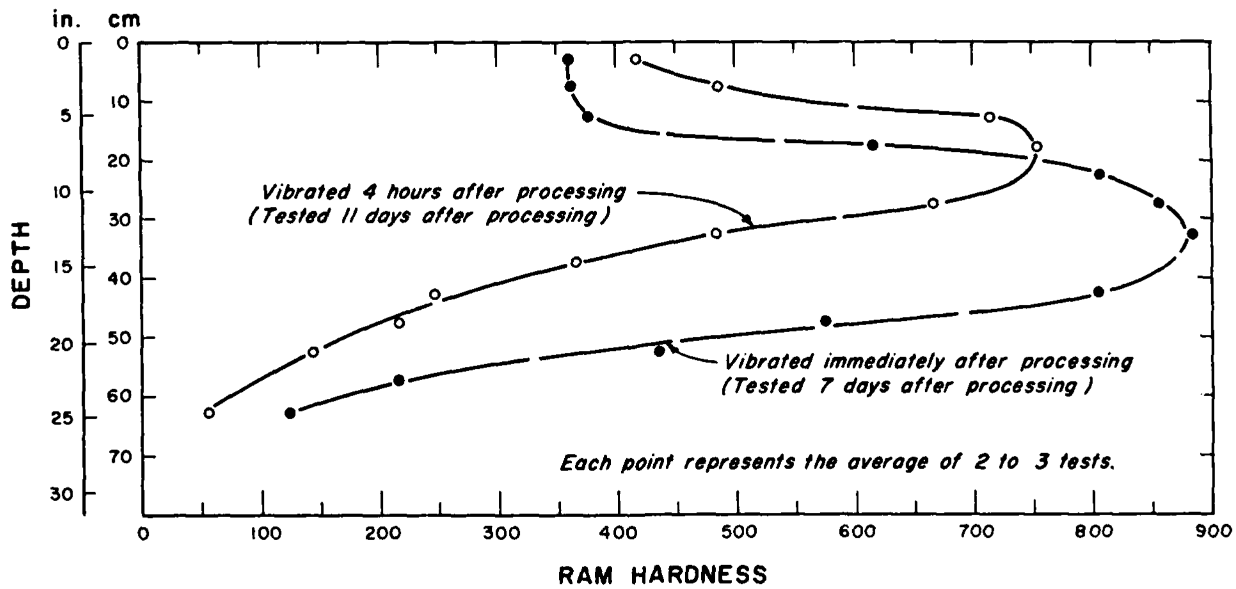


Figure 95. Effect of vibratory compaction immediately and 4 hours after processing (Wuori 1965).

may affect only the top few centimeters of the snow pavement.

A plate or shoe-type vibratory compactor, developed by NCEL (Moser and Gifford 1962b), is shown in Figure 96. The frequency capability of this unit was from 380 to 1000 cpm, and the ground pressure was 0.14 kg cm^{-2}. The compactor was attached behind a finishing drag with the hydraulic power pack installed on the drag. The tandem drag and compactor arrangement was towed by a tractor. The best results were obtained at a vibration frequency between 600 and 700 cpm at a forward speed of 24 m min^{-1}. A higher forward speed resulted in a rippled surface. The compaction effectiveness extended to a depth of 40 cm.

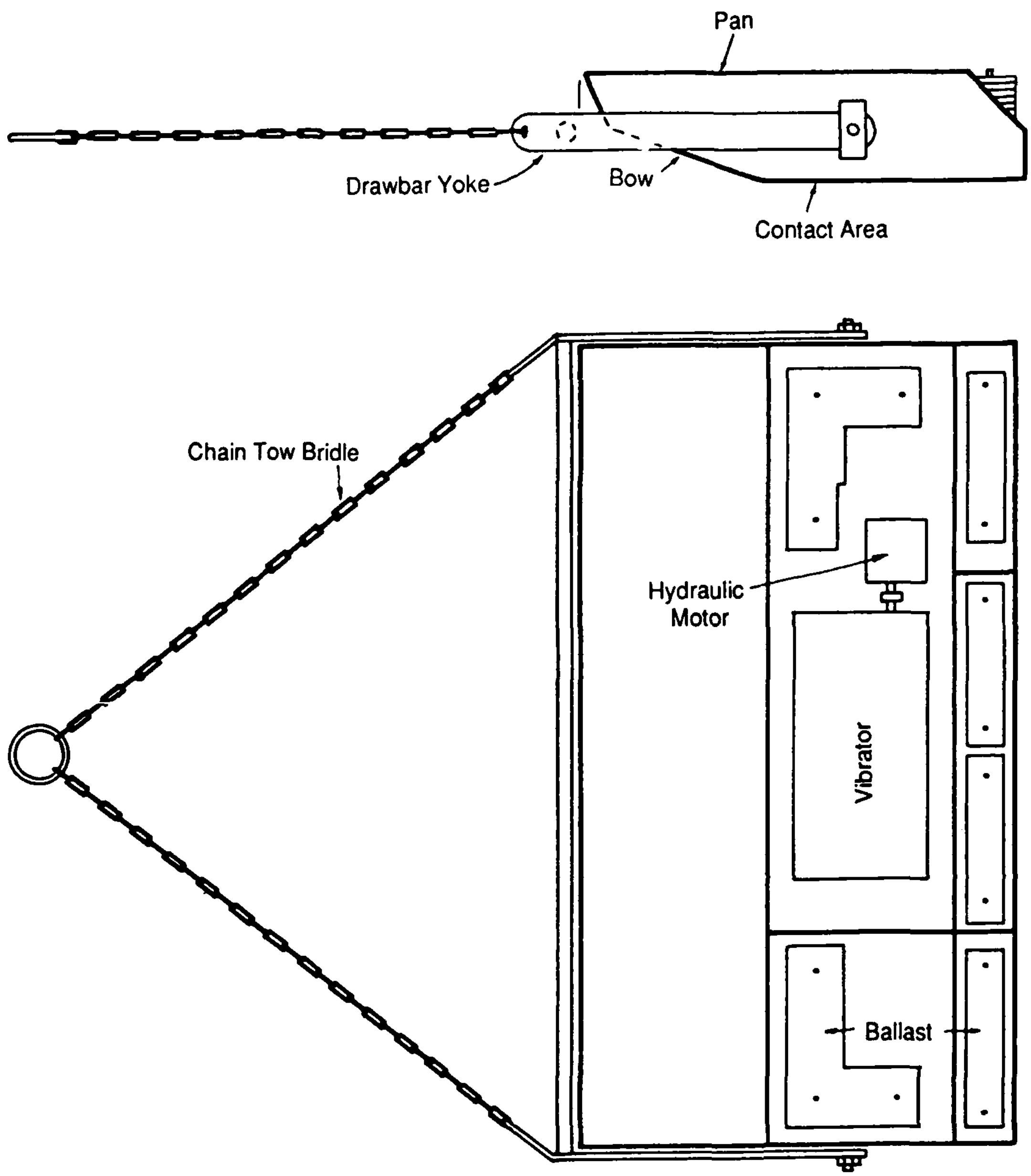


Figure 96. NCEL shoe-type vibratory compactor.

A rolling-type vibratory compactor, developed by NCEL (Moser and Gifford 1962b), is shown in Figure 97. The total weight of the unit, including the power package, was 3700 kg. The vibrating frequency of the 1.3-m-diameter, 1.8-m-long steel roller could be varied from 1290 to 2320 cpm by changing the engine speed. The best results were obtained at a travel speed of approximately 100 m min^{-1} and a vibrating frequency of 2000 cpm at temperatures of −10° to −15°C. When used within 2 days after processing and leveling, the compaction effectiveness extended to approximately 30 cm, the most significant strength increase being at the 10- to 20-cm depth.

A smaller, rolling-type vibratory compactor, used during snow pavement construction tests in Upper Michigan, is shown in Figure 98.

Generally, rolling-type vibratory compactors are not as suitable as flat vibratory compactors. Because of their relatively high ground pressure, roller sinkage is excessive if used soon after processing and leveling (when compaction of the still unbonded snow is most beneficial). When used after considerable hardening of the snow has occurred, the vibratory roller sinkage is consequently decreased, but so is the vibratory compaction effectiveness.

Figure 97. NCEL vibratory roller. (Official photograph, U.S. Navy.)

Figure 98. Small rolling-type vibratory compactor.

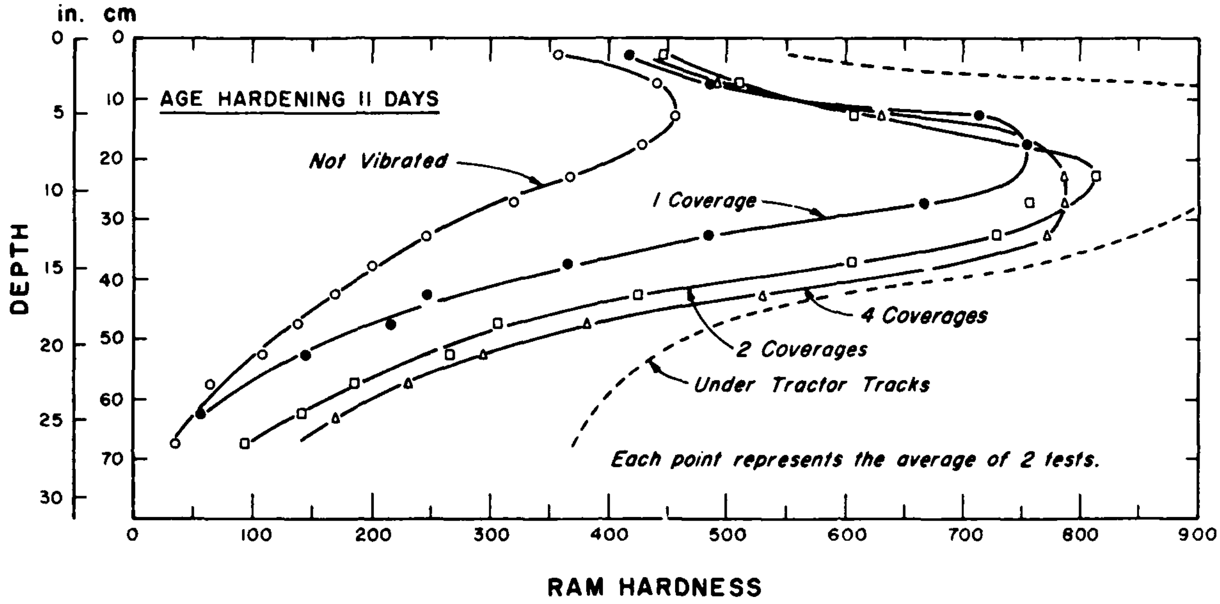


Figure 99. Effect of vibratory and tractor track compaction (Wuori 1965).

Figure 100. NCEL snow leveling drag. (Official photograph, U.S. Navy.)

In the USSR STM-2 snow processor (Fig. 71), a shoe-type vibratory compactor is incorporated into the processing unit so that the compaction is accomplished immediately after the heat-processing.

Tractor tracks

During various snow pavement construction tests, it was observed that the tracks of heavy tractors (D-6 to D-8) were frequently more effective compactors than the specialized compaction equipment towed by the tractors (Wuori 1960, 1963a, 1963b). The 137-cm-wide tracks of a low-ground-pressure (LGP) D-8 tractor and the 35 metric-ton gross weight, combined with the vibration caused by the bogie wheels passing over the track pads, increased the surface hardness and extended the compactive action deeper than other compaction equipment (Fig. 99).

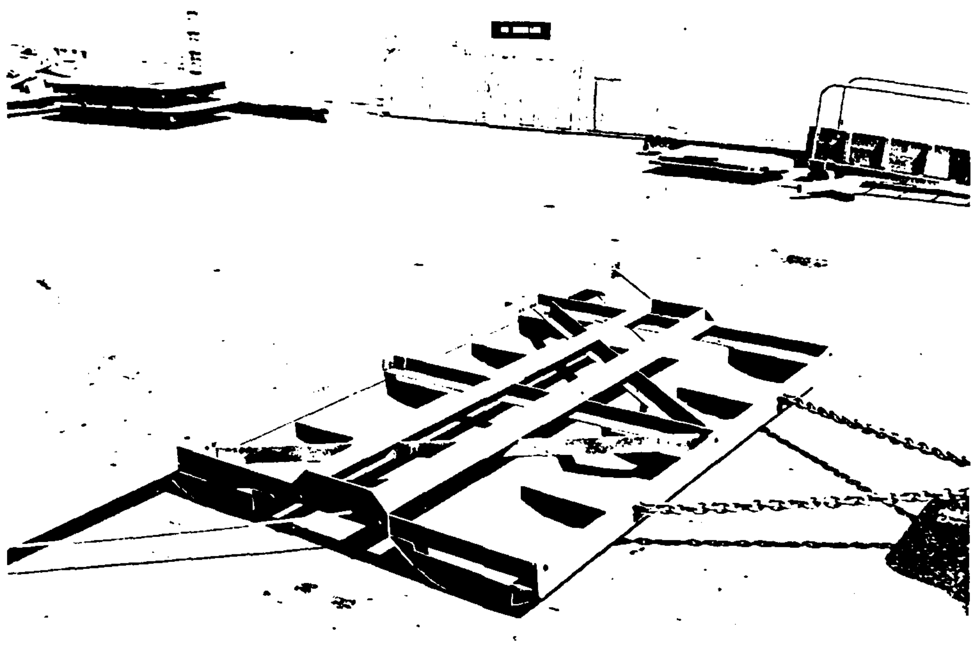


Figure 101. NCEL snow finishing drag.

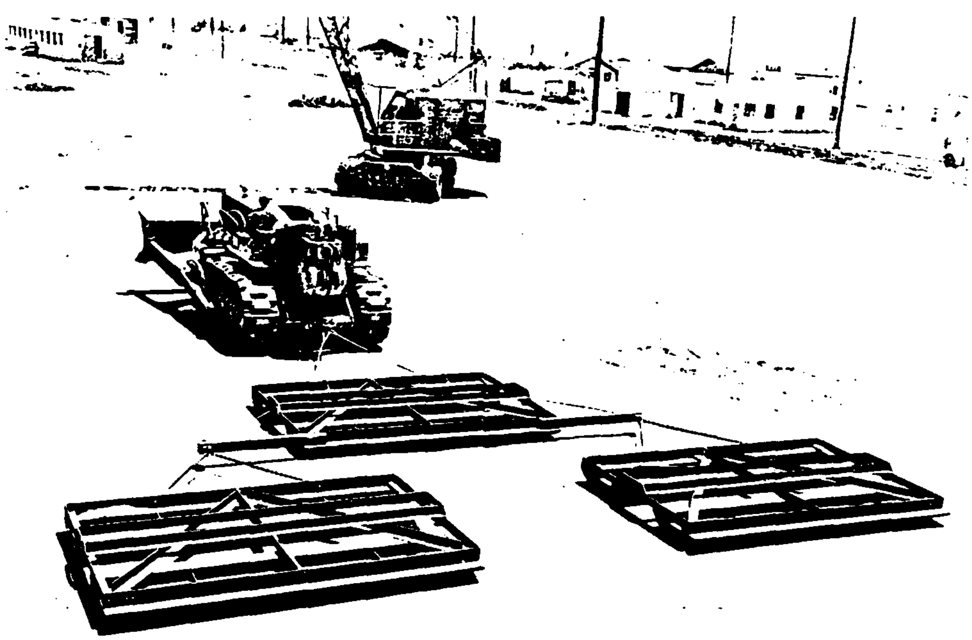


Figure 102. Three-gang tow arrangement of finishing drags.

Drags

After processing, leveling and compaction, the snow pavement surface is seldom suitable for wheeled vehicle traffic or aircraft operations and requires some degree of finishing to obtain a smooth surface. A metal-faced wooden drag (Fig. 100 and 56) is suitable for shaving off surface irregularities. This type of drag is also used for snow pavement maintenance to level off drifts and uneven snow accumulation.

For final finishing of a snow pavement surface, a smooth, curved-bottom metal drag is used (Fig. 101). For runway pavement finishing, a three-gang tow arrangement, as shown in Figure 102, can be used. The characteristics of the finishing drag, used by NCEL, are shown in Figure 103 (Camm 1960). Improvised drags, such as the one shown in Figure 57, could be used as finishing drags.

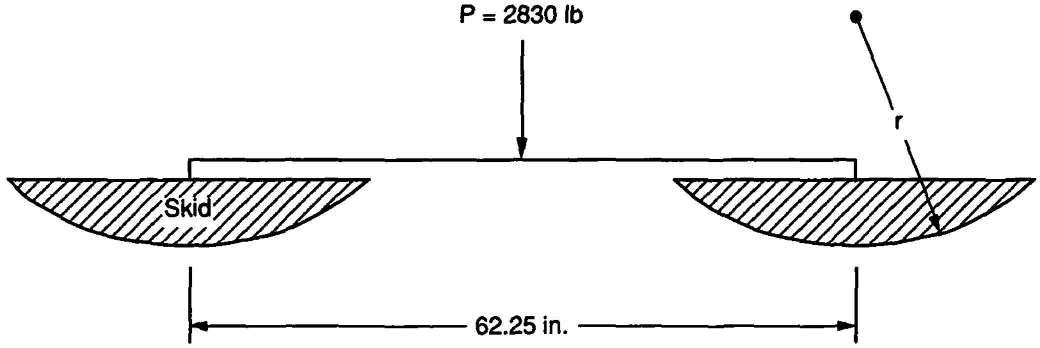


Figure 103. Characteristics of snow finishing drag.

Figure 104. Finishing drag towed by tractor. (Official photograph, U.S. Navy.)

Ordinarily it is preferable to tow the finishing drags with a wheeled vehicle if the necessary drawbar pull can be generated by the vehicle and if the snow has hardened sufficiently to permit wheeled traffic. However, since it is more beneficial to accomplish the surface finishing soon after leveling and compaction, low-ground-pressure tractors are required to tow the finishing drags (Fig. 104).

Additives

The strength of compacted snow can be increased by adding sawdust or wood pulp (Abele 1963c, Perutz 1948). Figure 105 shows the increase in the modulus of rupture of a snow and wood pulp mixture at −17°C as a function of the percentage of wood pulp.

The addition of sawdust to the surface layer of a snow pavement was investigated during the construction of snow runway test strips in Upper Michigan. The mixing of the top 16 cm of a 1-day-old processed snow pavement with 8% (by volume) of sawdust, using a pulvimixer and then a vibratory compactor, resulted in a 10–20% higher strength (after 2 weeks) than that in the control section, which was processed and compacted without sawdust (Fig. 106).

Better results can be obtained if the 10- to 15-cm-thick surface snow layer is mixed with a sawdust–water slurry. This method was used to construct a small pavement test section in Greenland. A mixture of 80% processed snow, 10% sawdust and 10% water (percent-

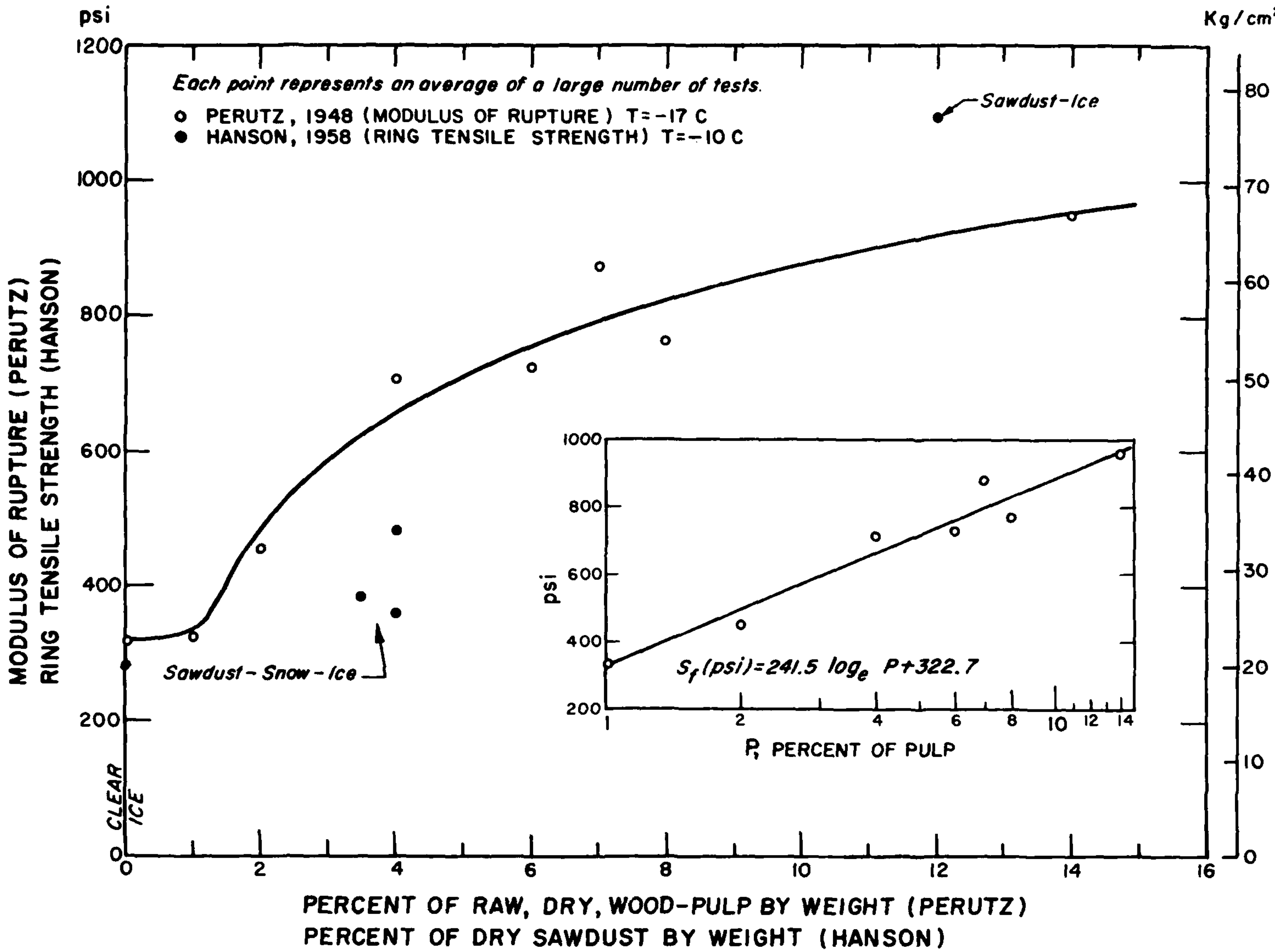


Figure 105. Snow strength as a function of the percentage of wood pulp.

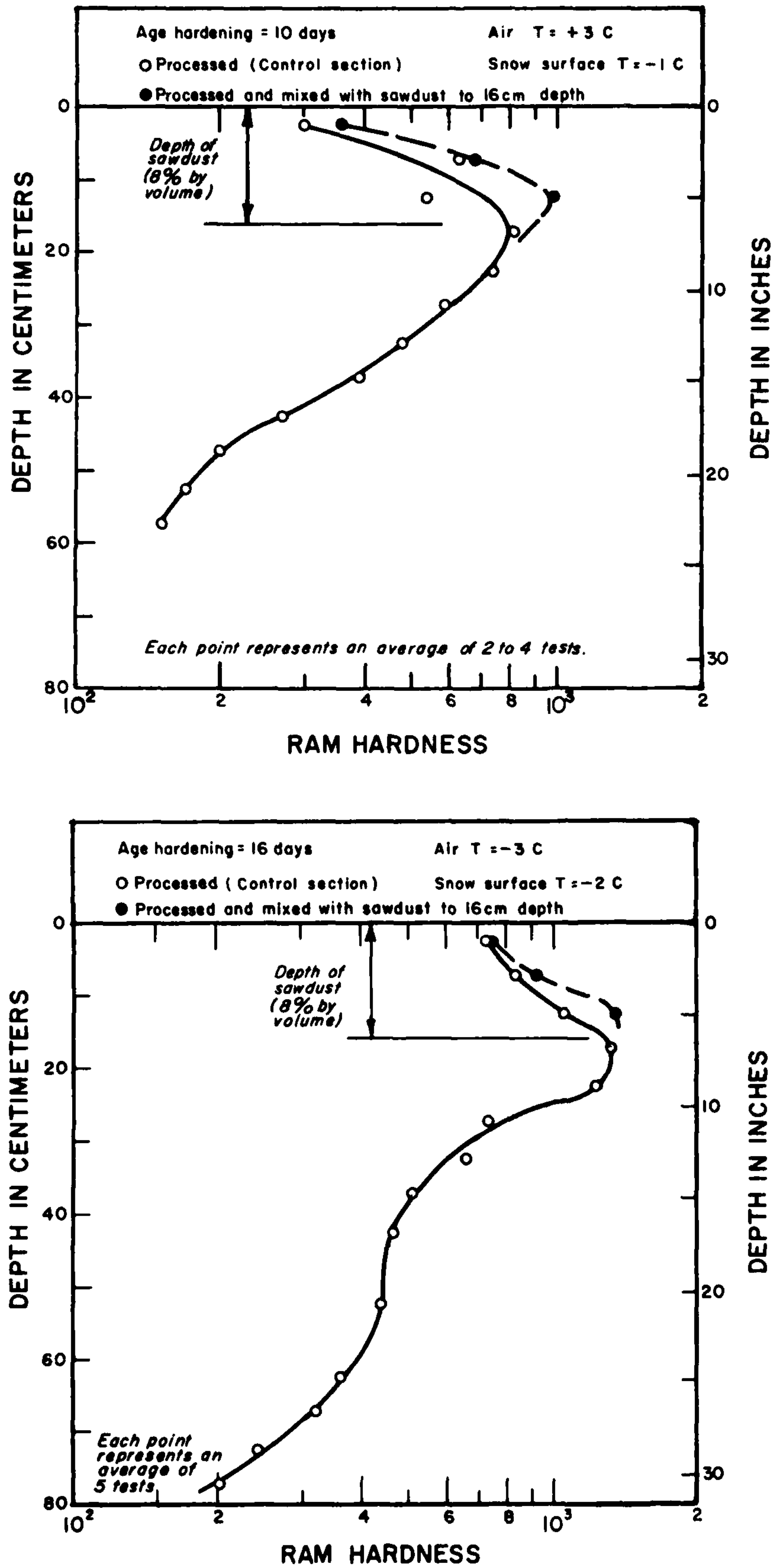


Figure 106. Ram hardness profiles of processed snow with and without sawdust (Abele 1964a).

Figure 107. NCEL snowplow sidecasting snow for an elevated road. (Official photograph, U.S. Navy.)

ages by volume) produced a very strong, high-density (0.78 g cm^{-3}), low-skid wearing surface (Abele 1963c).

More recently tests on sawdust–snow mixtures were conducted in Antarctica (Lee et al. 1988, Wuori and Lee 1988). Test results showed an increase in strength in the pavement test sections where sawdust, 5–10% by volume, had been added to the snow.

Sawdust can also be used as an effective cover on snow pavements. NCEL constructed a compacted snow parking lot for the 1960 Olympic Winter Games at Squaw Valley, California (Dykins et al. 1958, Coffin 1959, Moser 1962). A 1-cm-thick layer of sawdust spread on top of the snow pavement surface provided good traction for cars and, by insulating the snow pavement from direct solar radiation, reduced the rate of ablation during warm periods and helped to extend the useful life of the parking lot.

To protect the snow pavement surface, other materials have been investigated (Stehle 1964, 1966), particularly urethane foams (Goodyear Aerospace Corp. 1964, 1965). Although various surface protection materials and additives have shown promise during small-scale tests, the problems with required application techniques and the effort and additional logistics burden involved in full-scale snow road and runway construction usually outweigh the benefits. Also, there is the continuous problem of new snowfall covering the pavement surface, minimizing the benefits of a specially prepared protective surface cover or the usefulness of an additive-reinforced snow surface layer.

The following examples illustrate the logistics burden of providing a minimal sawdust reinforcement for a snow pavement. A 1-km-long, 30-m-wide runway that will have sawdust 1 cm thick mixed with the top 10-cm processed and compacted snow layer (10% by volume) would require amount 300 m^3 of sawdust, or between 50 and 75 tons (depending on the sawdust density). A 1-km-long, 6-m-wide road would require 60 m^3 km^{-1}, or between 10 and 15 tons km^{-1}.

Construction procedures

Proper construction procedures are important in snow road and airstrip development to use or implement techniques that will optimize snow strengthening factors and extend road or runway life.

In either a perennial snowfield or an annual seasonal snow area, snow drifting and accumulation may be a problem. It will be of much value to elevate the processed surface so that subsequent snow removal will be reduced. Figures 107 and 108 illustrate procedures for elevating a roadbed or runway by casting snow from a borrow pit area on each side. Figure 109 illustrates the finished elevated surface, which has a depressed area on each side to serve as a snow trap. Careful sloping of the roadbed sides will minimize snow drifting or accumulation on the surface. Figure 110 shows another typical cross section of an elevated snow runway, illustrating the procedure used by the U.S. Navy in Antarctica, when the pulvimixer is used as the snow processor (Moser 1964a).

The continuity of the construction procedure, particularly the importance of the minimum possible time between snow processing and compaction, has been discussed previously. As an example, Figure 111 compares the age-hardening curves of processed snow com-

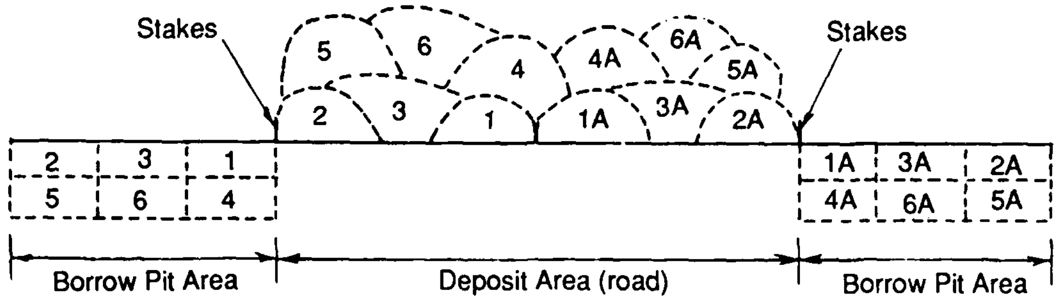


Figure 108. Snowplow pass sequence for an elevated snow road.

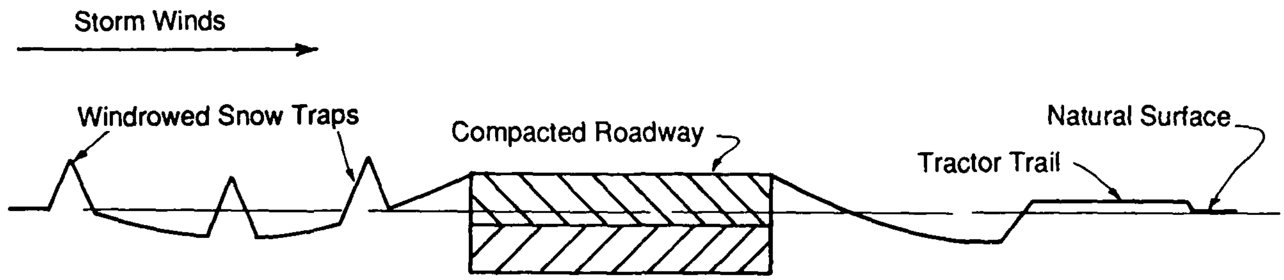


Figure 109. Typical cross section of a two-layer elevated snow road (NCEL).

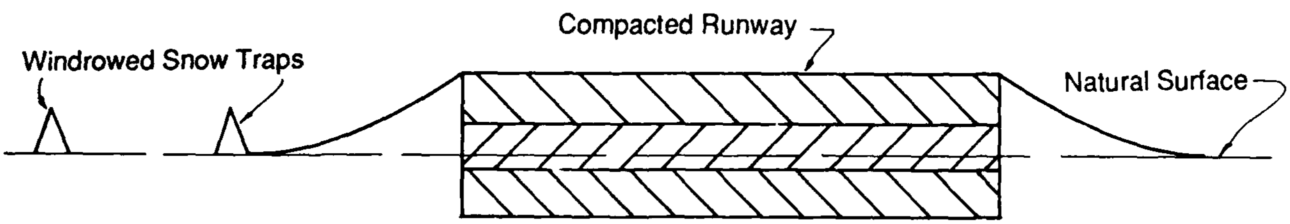


Figure 110. Typical cross section of a three-layer elevated snow road (NCEL).

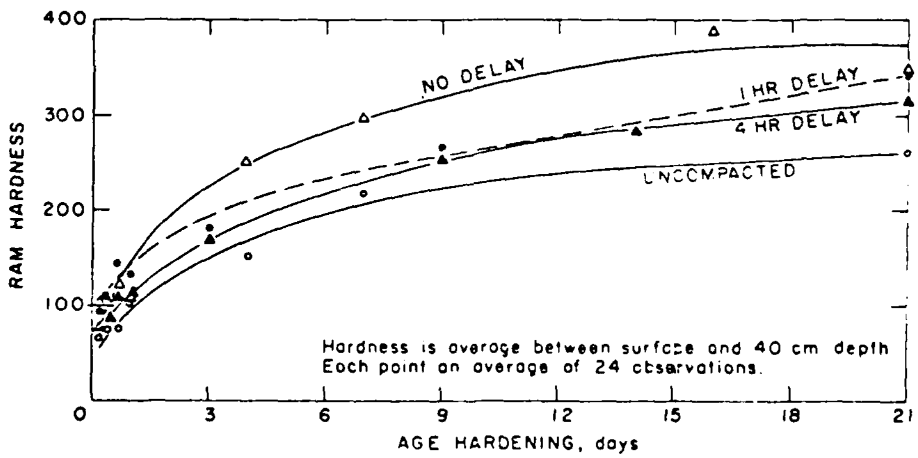


Figure 111. Age-hardening of vibratory compacted processed snow.

pacted with a vibratory compactor immediately after and 1 and 4 hours after processing. The construction of full-size, high-strength snow runways requires careful coordination between the various operations and the equipment used, primarily because of the width of pavement required. The coordination and timing of operations are less complex for constructing a long, narrow pavement (snow road) than those required for a relatively short but wide pavement (runway).

Figure 112 and Table 5 show various sequences of operations used by the U.S. Navy (Reese 1955, Moser 1962). Table 6 illustrates the construction time estimate for a small (3000- × 100-ft) runway, using a Peter plow snow processor.

The previous discussion on operation and maintenance of expedient snow pavements also applies to high-strength pavements.

Table 5. U.S. Navy snow pavement construction procedures. (After Reese 1955.)

Technique	*Process*	*Treatment*
Precompaction preparations	Compressive compaction	2 passes with compaction roller
	Wait	12–24 hours
	Leveling	2–3 passes with snow plane
	Compressive compaction	2 passes with compaction roller
	Wait	12–24 hours in below-freezing air temperatures before further treatment
Depth-processing	Mixing	3 passes with snow mixer with not over 1–2 hours between passes
	Leveling	1 pass with snow-leveling drag to remove windrows
	Compressive compaction	3 passes with compacting roller
	Wait	3 days minimum in below-freezing air temperatures before further treatment
Double depth-processing	Primary	As described under depth-processing
	Wait	3 days minimum before further treatment
	Secondary	Reprocess as described under depth-processing
	Wait	8 days minimum before further treatment
Surface-hardening	Rolling	2 passes with surface-hardening roller
	Finishing	2 passes with snow-finishing drag
	Wait	20–24 hours in below-freezing air temperatures before use
Layered compaction	Precompaction preparation	As described above
	Double depth-processing	As described above
	Wait	8 days in below-freezing air temperatures before further treatment
	Fill	Place a 2-ft cover of new snow over first compacted layer
	Precompaction preparation	Level and roll new snow cover as described above
	Double depth-processing	As described above
	Wait	8 days in below-freezing air temperatures before further treatment
	Fill	Place a 2-ft cover of new snow over second compacted layer
	Precompaction preparation	Level and roll new snow cover as described above
	Double depth-processing	As described above
	Wait	8 days in below-freezing air temperatures before further treatment
	Surface hardening	Finish third layer of compacted snow as described above
	Wait	20–24 hours in below-freezing air temperatures before use

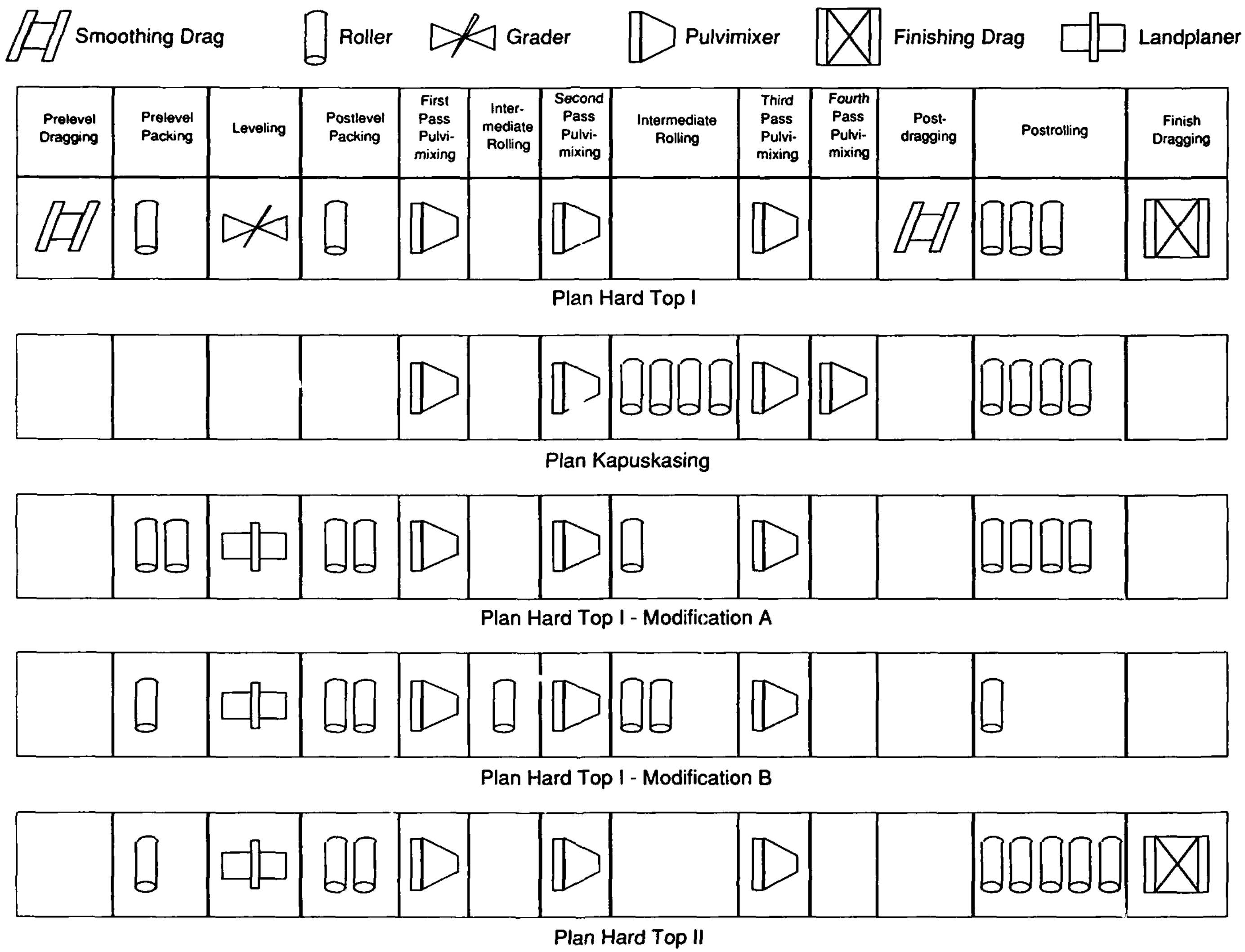


Figure 112. U.S. Navy snow pavement construction procedures (Reese 1955).

Table 6. Construction time estimate for a 3000- × 100-ft runway.

For initial calculations, assume:	
Runway length	3000 ft
Runway width	100 ft
Effective processing width per pass (disaggregating, leveling, compacting) to permit sufficient overlap	5 ft
Construction equipment speed	250 ft/min
Two bulldozers available: one for disaggregating, one for leveling and compacting	
Realistic length of work day	5 hr
	Cumulative time
Disaggregating: 3000 ft at 250 ft/min = 12 min/pass; use 15 min/pass including turnaround time; 100-ft width at 5 ft/pass = 20 passes	5 hr
Leveling and compacting: begin after the first few disaggregation passes; complete 2 hr after completion of disaggregation	7 hr
Final grading: Complete 2 hr after completion of leveling and compaction	9 hr
Miscellaneous: preparations, engine startup, etc.	10 hr
Safety factor of 2	20 hr or 4 days
Initial site preparation (2 days)	6 days

SNOW PAVEMENT EVALUATION AND DESIGN CRITERIA

The strength of a snow pavement must be carefully evaluated to determine its bearing capacity in terms of wheel loads. This evaluation should begin a few days after processing and continue throughout the snow-hardening period.

The most convenient implement for evaluating snow pavements is the Rammsonde cone penetrometer. It is easily used by one person, and a large number of hardness strength profiles can be made in a relatively short time, which enables a determination of snow pavement strength uniformity as well. For example, Figure 113 shows ram profiles of processed snow pavements at various degrees of compaction with bulldozer tracks. Figure 114 shows profiles of a snow pavement at progressively longer hardening times after processing and compaction (Abele 1968). Figure 115 illustrates the age-hardening process of a snow pavement (at the 15-cm depth) that was compacted with an LGP D-8 tractor (Wuori 1963a). Figures 116 and 117 show typical density and ram hardness profiles, respectively, resulting from various processing and compaction methods.

Test rigs that are capable of simulating actual aircraft wheel loads have been used for traffic tests on snow pavements (Fig. 118 and 119). Ram hardness profiles were obtained at failure and non-failure areas for various aircraft tire, wheel load, contact pressure and traffic repetition conditions. The snow hardness data were correlated with the aircraft wheel traffic test results to establish the required strength properties of snow pavements for aircraft operations. An example of a pavement surface failure is shown in Figures 120 and 121.

Actual aircraft tests, primarily with a C-130 with the skis retracted (Fig. 122), have been performed in Antarctica to verify the required ram hardness strength criteria. Figure 123 shows a C-124 aircraft on a processed snow runway in Greenland.

A test rig with a high wheel load capacity is, of course, the most reliable method for evaluating the snow runway strength characteristics. However, rarely would such a rig be available, and the evaluation of a snow pavement would ordinarily have to depend on a simple manual device, such as the Rammsonde cone penetrometer.

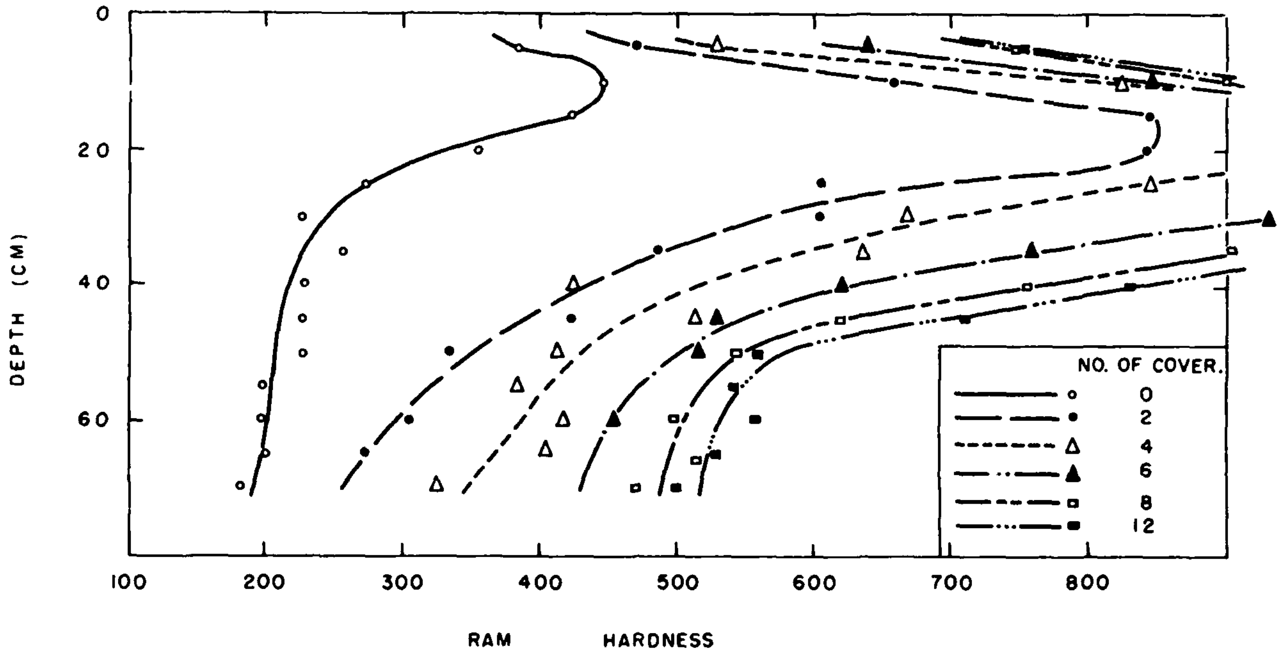
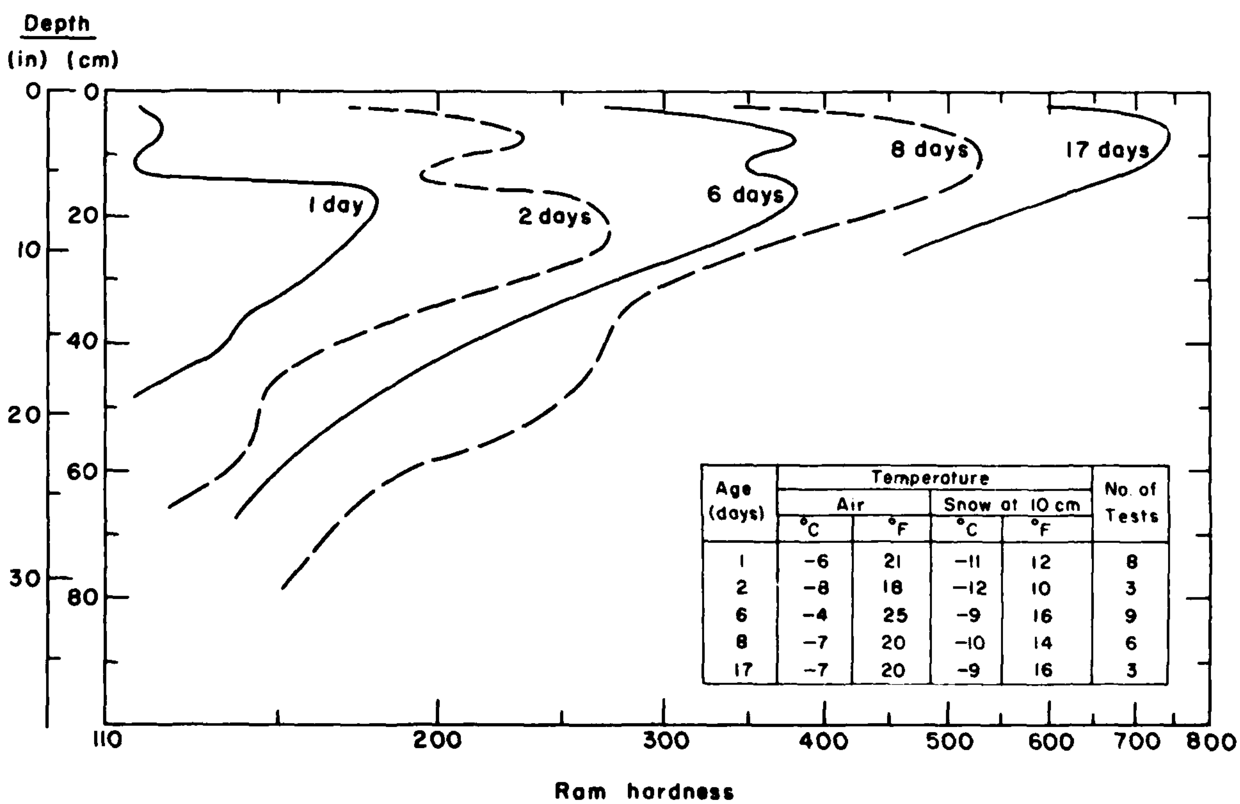
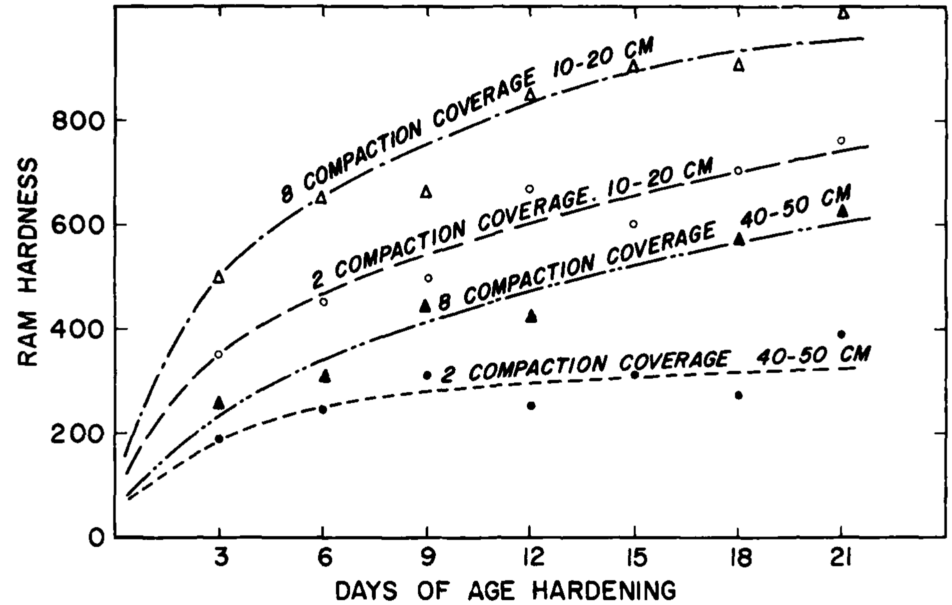


Figure 113. Ram hardness profiles of processed snow pavements compacted with D-8 LGP tracks, after 3 weeks of age-hardening (Wuori 1963a).

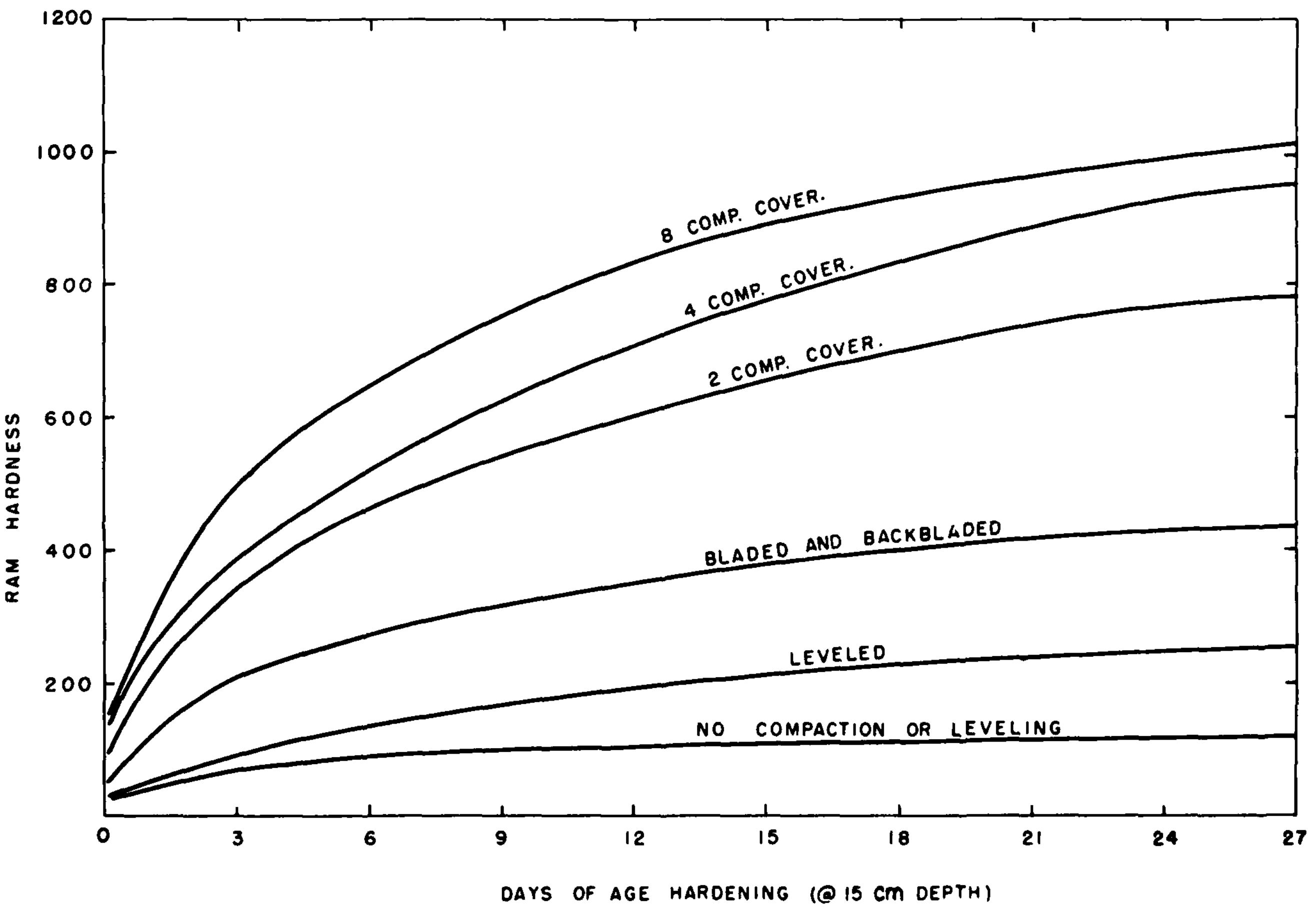


Age (days)	Temperature: Air °C	Air °F	Snow at 10 cm °C	Snow at 10 cm °F	No. of Tests
1	−6	21	−11	12	8
2	−8	18	−12	10	3
6	−4	25	−9	16	9
8	−7	20	−10	14	6
17	−7	20	−9	16	3

Figure 114. Ram hardness increase with time for a processed, compacted snow pavement (Abele 1968).



a. Hardening at two depths.



b. Effect of degree of compaction.

Figure 115. Age-hardening curves of processed snow compacted with D-8 LGP tractor tracks (Wuori 1963a).

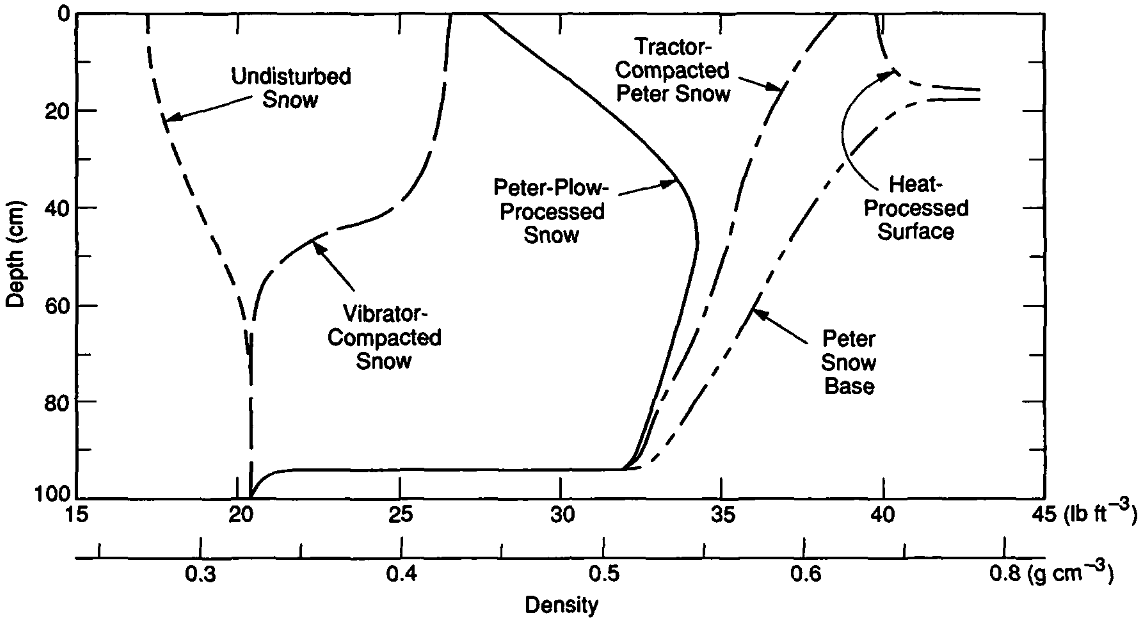


Figure 116. Typical density profiles resulting from various compaction methods.

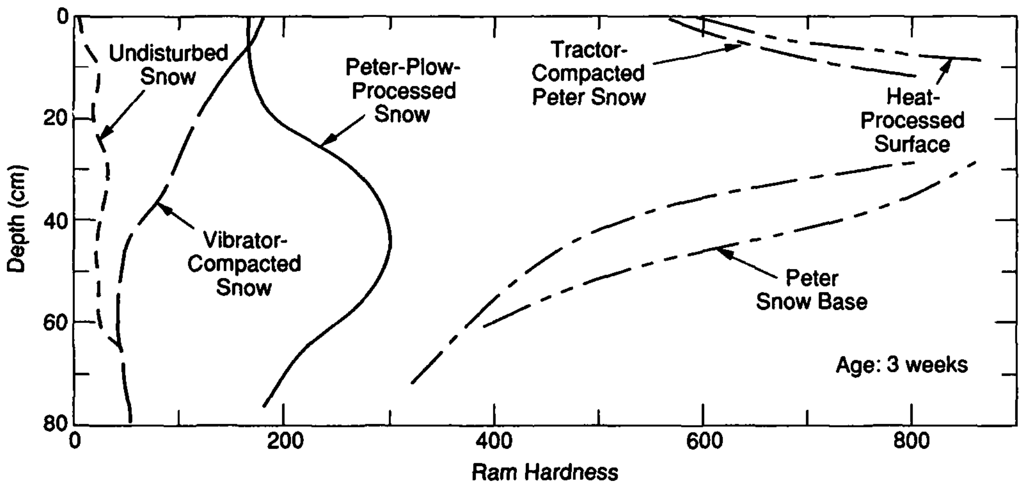


Figure 117. Typical ram hardness profiles resulting from various compaction methods.

Figure 124 illustrates the type of ram hardness profiles that can be achieved with a variety of snow stabilization methods and the corresponding wheel loads and contact pressures that can be supported by such snow pavements.

Idealized hardness or strength profiles required for a snow pavement to permit operations of various types of aircraft are shown in Figure 125. Usually, the highest strength in a processed snow pavement is achieved at some distance below the surface (15–30 cm), while ideally the maximum strength is required at the surface. This illustrates one of the principal problems in constructing a suitable snow pavement for wheel loads with high contact pressures. While the required snow strength below 20 or 30 cm can be easily obtained with ordinary processing and compaction methods, the necessary surface strength (ram hardness above 1000) for aircraft such as KC-135, C-5A and C-141 (contact pressures in the 9- to 11-kg cm^{-2} or 130- to 150-psi range) requires extensive surface-hardening procedures, such as the application of heat or water and high-pressure compaction.

Figure 118. Test rig for simulating aircraft wheel loads (CRREL).

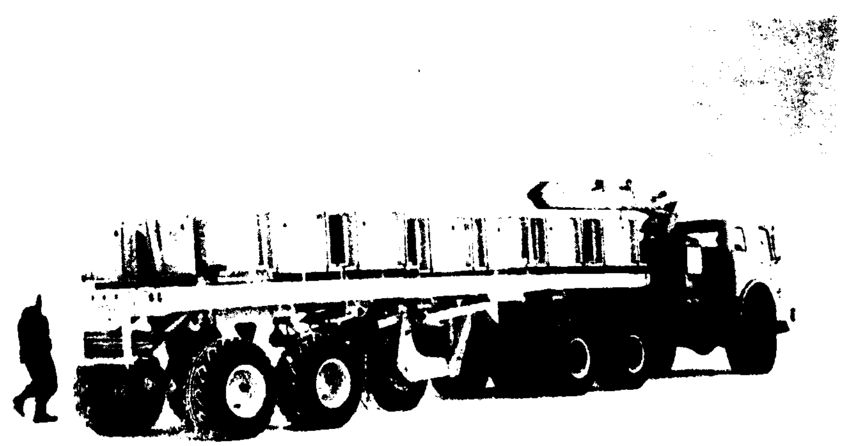


Figure 119. Test rig for simulating aircraft wheel loads (NCEL). (Official photograph, U.S. Navy.)

Figure 120. Surface failure produced with a simulated aircraft wheel load. (Official photograph, U.S. Navy.)

Figure 121. Typical surface failure areas on a snow runway. (Official photograph, U.S. Navy.)

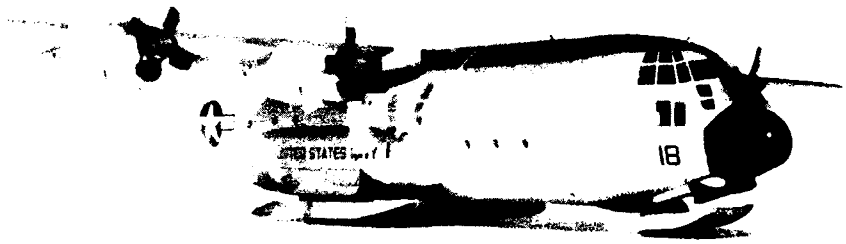


Figure 122. C-130F aircraft after a wheeled landing on a snow runway at McMurdo. (Official photograph, U.S. Navy.)

Figure 123. C-124 aircraft on snow runway in Greenland.

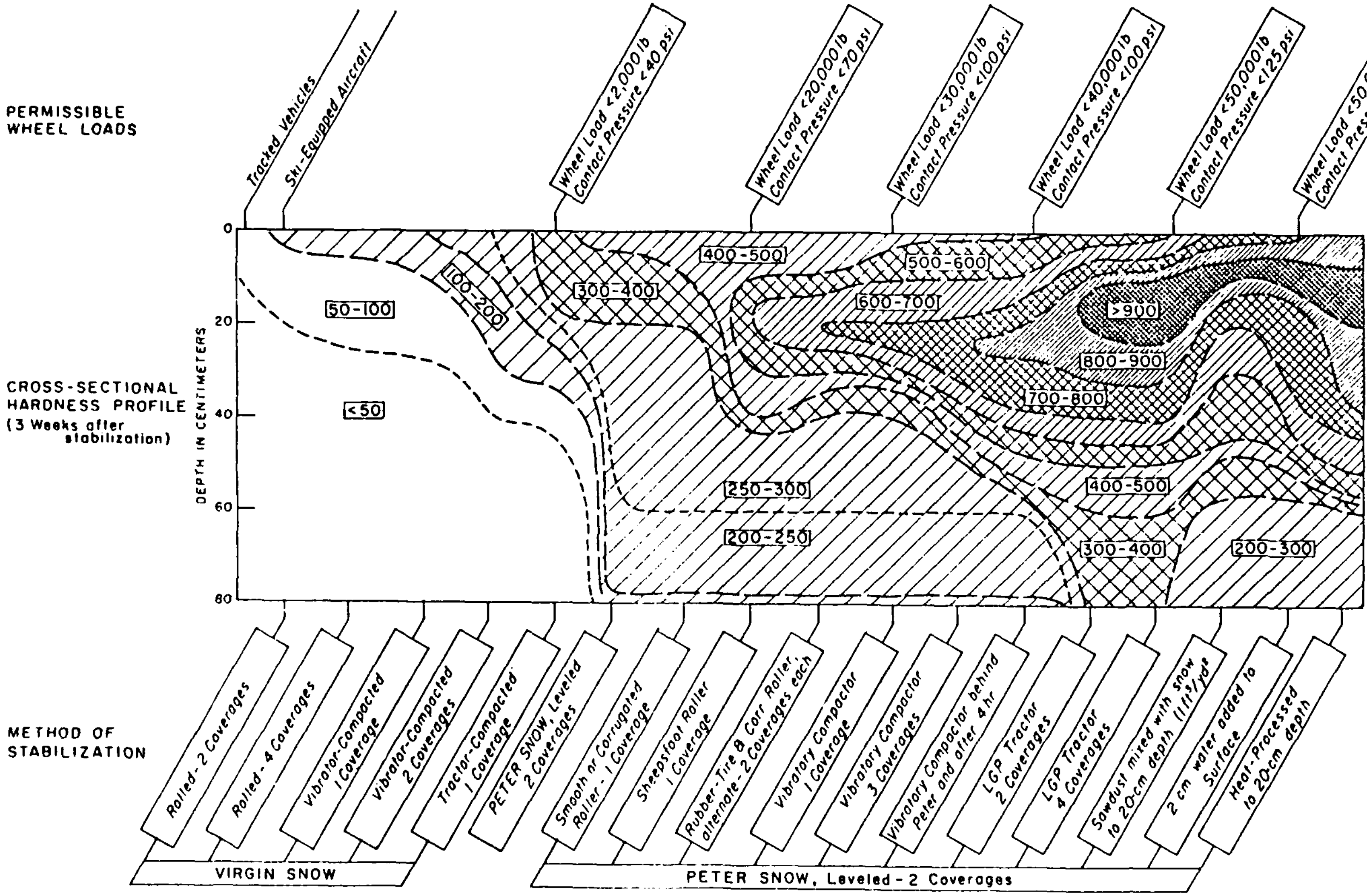


Figure 124. Ram hardness profiles obtained with various snow stabilization methods and the corresponding load-supporting capacity (Wuori 1963b).

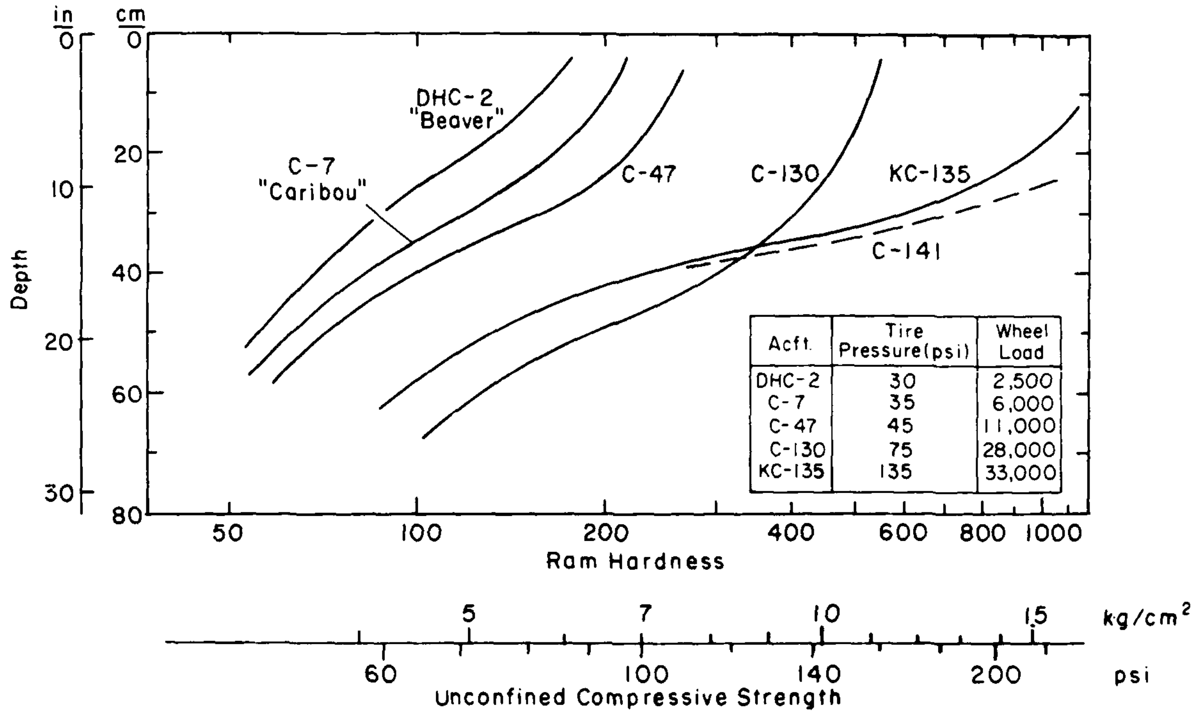


Figure 125. Required snow hardness or strength profiles for support of various aircraft.

The nomograph in Figure 126 permits an estimate of the snow pavement surface strength required for any tire contact pressure and wheel load combination. Starting from the scale at the left, which shows the mean contact pressure (usually approximately equivalent to the tire inflation pressure), a line is drawn through the appropriate wheel load (single wheel) on the next scale to the pivot line. From this point, the line is continued through the scale showing the number of wheel coverages, which represents not only the aircraft wheel arrangement (n = 2 for tandem wheels; for a C-5A aircraft $n = 4$), but also a case where the pavement surface is subjected to repetitive wheel passes in quick succession over the same spot. (Ordinarily this is not the case on runways, but it can occur on roads because of channelized traffic).

The intersection of the line with the ram hardness scale indicates the hardness required in the snow pavement surface layer, the thickness of which is r, the equivalent circular contact area radius. That is, a tire with a larger contact area requires a thicker surface layer than a tire with a smaller contact area, due to the pressure bulb effect. Ordinarily the value of r for aircraft tires is less than 30 cm (12 in.); therefore, for practical purposes, the required snow strength obtained from the nomograph pertains to the strength required in the "top foot" of the pavement strength profile. The strength required at any depth below the surface layer can be assumed to be in accordance with the Boussinesq stress distribution curve (Fig. 45).

In the nomograph (Fig. 126), the required strength properties are also shown in terms of unconfined compressive strength and CBR, on scales adjacent to the ram hardness scale. Also shown are examples of how the required strength is determined for various aircraft. The load characteristics of the aircraft with the corresponding snow pavement strength requirements, obtained from the nomograph, are shown in Table 7.

The effect of the tire contact area on the required strength profile is illustrated by the curves for the C-130 and KC-135 aircraft in Figure 125. The C-130, having a much larger tire contact area than the KC-135, requires a thicker surface layer, resulting in a required strength profile that diminishes at a lower rate than that for the KC-135. But because of the much higher contact pressure, the KC-135 requires a much stronger, although thinner, surface layer; thus, the two profiles intersect at a depth of 35 cm.

Technical data in the Soviet literature related to snow pavement characteristics are usually confined to snow density data. Occasionally values are given in units of strength (kg cm^{-2} or pascals), but it is not clear how these values were obtained. It has been difficult, therefore, to evaluate the strength properties of Soviet runways in Antarctica or to compare the results of their current construction methods with those of others. With very few exceptions (Fig. 71), illustrations of Soviet snow runway construction equipment are not available.

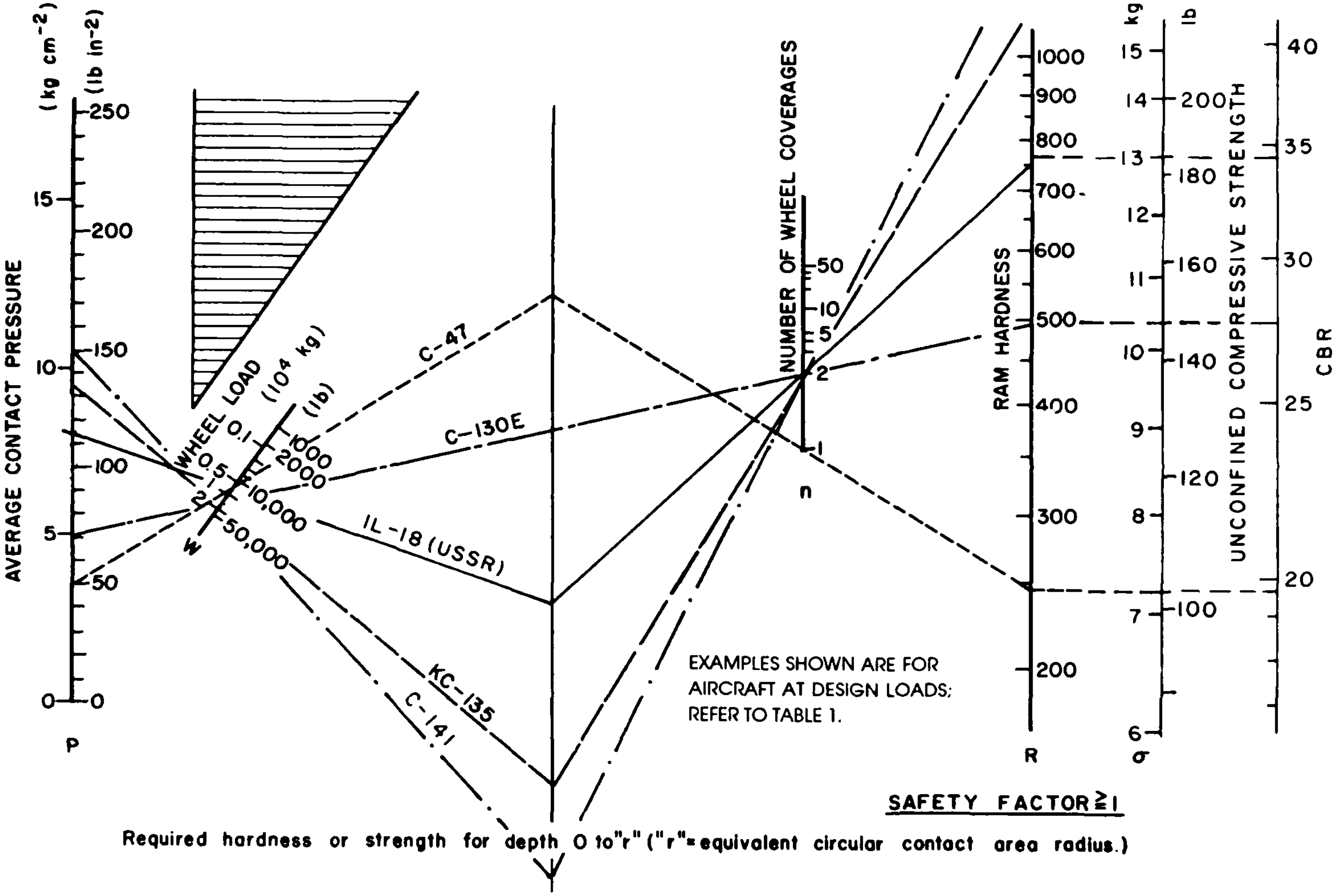


Figure 126. Nomograph for determining snow pavement surface strength for any wheel load condition.

Table 7. Aircraft wheel load characteristics and required snow pavement strength.

Aircraft and type of gear	n*	*Aircraft specifications* Gross weight (lb)	Wheel load (lb)	Tire contact area (in^2)	Tire pressure (psi)	*Required strength characteristics for top 12 in. of snow pavement* R	σ (psi)	CBR
C-47 (single)	1	25,000	11,800	238	45	250	105	20
C-124 (dual)	1	194,500	38,600		78	400	135	25
C-130 (single tandem)	2	135,000	28,500	405	70	500	150	28
KC-135 (dual tandem)	2	250,000	33,500	250	134	>1000	220	42
C-5A	4	732,500	26,000	190	150	>>1000	250	45
C-141 (dual tandem)	2	318,000	40,000		150	>>1000	250	47
IL-18 (USSR; dual tandem)	2	134,600	15,000		114	750	185	35

* *n* = number of wheel coverages on same area

FEASIBILITY OF CONSTRUCTING A HIGH-STRENGTH SNOW RUNWAY AT THE SOUTH POLE

During recent years, serious consideration has been given to expanding the use of heavy aircraft in Antarctica to improve logistics and supply activities between McMurdo, where ice runways are used for C-141 operations, and the South Pole Station. Current air operations beyond McMurdo are limited to ski-equipped C-130 or smaller aircraft. The construction of a snow runway at the Pole, capable of supporting C-141 aircraft in a maximum gross load condition, may not be impossible, but would be extremely difficult because of the low temperatures during construction.

Snow pavements requiring strength characteristics above a rammsonde hardness of 1000 (or unconfined compressive strength above 200 psi or CBR values approaching 40) are difficult to produce with practical construction methods. This can be achieved with dry-processing techniques (milled or pulvimixed snow, compacted with tractor tracks, vibrators and rollers) if temperatures during construction are in the -12° to -1°C range. As the temperature decreases, particularly below -18°C, the compaction effectiveness decreases, the rate of age-hardening (or sintering) decreases, and the operational problems of equipment increase.

Because of the low rate of the age-hardening process at the South Pole temperature conditions, a 1-year waiting period after construction may be required before C-141 aircraft operations could be considered. That is, if the construction of the runway can be successfully completed during one season, the hardening process may require a full season to progress to a stage where the snow strength approaches that required for C-141 aircraft.

The addition of water during snow processing has not been very successful, even at temperatures higher than those at the Pole. It has been extremely difficult to achieve a uniform snow–water mixture and therefore a homogeneous pavement. At temperatures comparable to those at the South Pole, this problem is further complicated by the difficulty of keeping water in a liquid form during application.

The application of heat directly to the snow during milling is somewhat less troublesome, but maintaining quality control to achieve a homogeneous pavement has been difficult. Mechanical problems with the heat application equipment have been frequent.

The use of landing mats on a processed snow pavement would provide the required load-bearing capacity for C-141 or similar aircraft. The need for close quality control during preparation of the snow base would be minimized. Accurate leveling of the snow surface would be important, and proper anchoring of the mats would be critical. The use of mats would, of course, also increase the logistics requirements quite significantly.

The two principal characteristics of the C-141 that determine the required snow strength are the high tire contact pressure (approximately equal to the tire inflation pressure of 150 psi) and the tandem wheel configuration, requiring the snow pavement design to consider two consecutive stress applications ($n = 2$ in nomograph, Fig. 126). The effect of wheel load is less significant, as shown in the example below.

The following example shows the effect of reduced wheel load and tire pressure on the required snow pavement surface strength in terms of unconfined compressive strength σ and rammsonde hardness R. The rammsonde cone penetrometer is not useful in snow pavements having unconfined compressive strength above 200 psi.

A C-141 with a maximum load has a gross weight of 318,000 lb, a wheel load of 40,000 lb and a tire pressure of 150 psi, resulting in a strength requirement of 250 psi (extrapolated from nomograph). A reduction of wheel load by 25% means that the wheel load is 30,000 lb and the tire press is 150 psi, resulting in $\sigma = 240$ psi, a strength reduction of only 4%. A reduction of tire pressure by 25% means that the wheel load is 40,000 lb and the tire pressure is 112.5 psi, resulting in $\sigma = 205$ psi and $R = 900$, a strength reduction of 18%. A reduction of both wheel load and tire pressure by 25% means that the wheel load is 30,000 lb and the tire pressure is 112.5 psi, resulting in $\sigma = 195$ psi and $R = 830$, a strength reduction of 22%. This strength requirement is slightly higher than that for the USSR IL-18 aircraft (gross weight condition), which has landed on a snow runway at Molodezhnaya.

The strength requirements for a C-5A aircraft are comparable to those of the C-141. Although the C-5A wheel load is less than that of the C-141 (Table 7), the wheel arrangement on the C-5A results in a wheel coverage number n of four, that is, four stress applications during each takeoff or landing.

A snow runway at the South Pole Station, capable of supporting C-141 aircraft, would require the following construction techniques and pavement characteristics. A 2-ft-thick pavement (located on top of the existing runway surface) should be constructed by processing with a pulvimixer and compacting with the tracks of a heavy tractor (several passes), followed by compaction with a vibratory compactor and several passes with a steel roller and leveling with a long-base planer. The resulting snow density of the pavement should be 0.6 g cm^{-3} or higher. Since it is unlikely that this type of dry-processed pavement, because of the low temperature at the South Pole, will attain the strength characteristics required for C-141 operations (rammsonde hardness above 1000, unconfined compressive strength above 200 psi), it will be necessary to either process the top 1-ft thickness of the pavement with some type of heat-application technique or use landing mats on top of the dry-processed pavement.

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APPENDIX A: USE OF THE RAMMSONDE CONE PENETROMETER

The Rammsonde instrument has been described earlier and shown in Figures 8 and 9. However, the procedure for its use and the method for calculating the ram hardness values may not be universally known; these are described below.

The Rammsonde is a cone penetrometer consisting of a hollow, 2-cm-diameter aluminum shaft with a 60° conical tip, a guide rod and a drop hammer. The standard cone has a diameter of 4 cm and a height of 3.5 cm; the total length of the penetrometer cone element (to the beginning of the shaft) is 10 cm. The guide rod, inserted into the top of the shaft, guides the drop hammer.

The hammer is raised by hand to a certain height which is read in centimeters on the guide rod, and then dropped freely (refer to Fig. 9). The depth of penetration is read from the centimeter scale on the shaft. The resistance to penetration of snow (commonly referred to as hardness) can be determined by observing either the amount of penetration after each hammer drop or the number of hammer drops (blows) necessary to obtain a certain penetration. In relatively hard, homogeneous snow it is usually more convenient to determine the number of blows needed to penetrate to some predetermined depth. Recording the number of hammer blows after each 5-cm depth increment is a convenient procedure commonly used. In layered and new, soft snows the more satisfactory procedure is to observe the amount of penetration after each hammer blow.

The standard Rammsonde kit contains two drop hammers, 1 and 3 kg in weight. A combination of one of the hammer weights and some drop height (0–50 cm) usually allows a suitable rate of penetration (between 1 cm per 5 hammer blows and 5 cm per blow) in a great variety of snows. Of course, the fewer combinations of hammer weight and drop height used during a series of tests, the more convenient the subsequent data reduction.

The ram resistance is computed from the following expression (for the standard 60° cone):

$$R = \frac{Whn}{x} + W + Q \tag{A1}$$

RAMMSONDE HARDNESS No. 15

Location ℄ Runway Test Position 5
Surface Descr. 0.5 cm new snow
Age Hard. 18 days Snow T -5°C Air T -4°C
Date 3 March 73 Time 1015 Observer G.A.
Remarks Overcast, calm

Hardness No. : $R = \frac{Whn}{x} + (W + qQ)$

W = Wt. of hammer (kg) h = Height of fall (cm)
q = No. of tube lengths n = No. of blows
Q = Wt. of one tube (kg) d = Depth of cone
x = Penetration resulting from n blows

W	h	n	d	x	$\frac{Whn}{x}$	W + qQ	R	
3	20	4	5	5	48	4	52 × 4.7	= 244
"	"	13	10	"	156	"	160 × 1.6	= 256
"	"	19	15	"	228	"	232	
"	50	7	20	"	210	"	214	
"	"	8	25	"	240	"	244	
"	"	6	30	"	180	"	184	
"	"	6	35	"	180	"	184	
"	"	5	40	"	150	"	154	
"	"	4	45	"	120	"	124	
"	"	4	50	"	120	"	124	

CRREL FORM 20 MAY 63 56

Figure A1. Rammsonde data card.

where R = ram resistance (kgf)
W = weight of drop hammer (kgf)
h = height of drop (cm)
n = number of hammer blows
x = penetration after n blows (cm)
Q = weight of penetrometer (kgf).

The ram resistance number R is an arbitrary index that indicates the resistance in kilograms offered by snow to the vertical penetration caused by ramming a metal cone of given dimensions. The resistance reading at any depth, obtained when the top of the cone is at that depth, represents the mean resistance through the depth increment between this and the previous reading.

Hardness values obtained with the 30° cone have to be multiplied by a factor of 2 (for the 0- to 10-cm depth) or 1.56 (for depths below 10 cm) to convert them into the standard ram hardness values. (This factor was determined by empirical, not theoretical, means; Fig. 33.)

Furthermore, because of the conical shape of the penetrometer head and the proximity of a free surface, the resistance values (obtained by the above equation) for the top 10 cm have to be multiplied by correction factors, as shown below.

		Correction factors	
Depth (cm)	Cone:	30°	60°
		0–5	4.0
4.7			
		5–10	1.6
1.6			
mean: 0–10		2.8	3.0

Figure A1 shows a sample data card that can be used for recording and calculating the ram hardness values.

REPORT DOCUMENTATION PAGE

Form Approved
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13. ABSTRACT (*Maximum 200 words*)

This monograph presents a complete review of all successful techniques that have been used to construct and maintain snow roads, trails and aircraft landing strips. The snow properties that must be considered prior to the construction process are identified, and the kinds of apparatus available for the measure of the properties are reviewed and assessed. A discussion of construction techniques is presented, which includes the types of snow pavements, the classification of roads by use, the classification of surface and subsurface strength, the considerations impacting on site selection, the various kinds of equipment that have been developed to construct and maintain the roads, and the additives that have been used to construct high-strength roads. The design criteria that have been established are cited.

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